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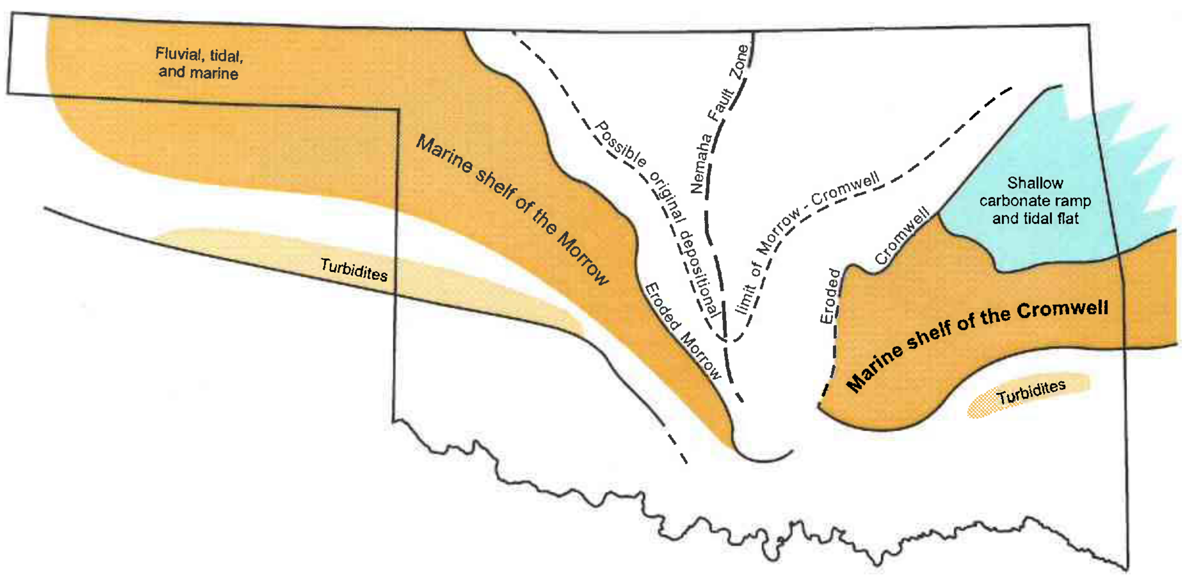
Cromwell Play in Southeastern Oklahoma

Richard D. Andrews



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by
Richard D. Andrews

Prepared for a one-day workshop, this volume is part of a continuing series that provides information and technical assistance to Oklahoma's oil and gas operators.

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Front Cover

Lower Morrow sandstone was deposited across much of western and southern Oklahoma most prominently in the form of marine bars. Deposition appears to have been affected by the Nemaha Fault Zone, which occurs along the western edge of the Cherokee Platform. The northern extent this structure was slightly positive during lower Morrow time, preventing or diminishing deposition in this area. Sediment supply corridors in the form of incised channels transported sand southward into the Anadarko Basin west of the Nemaha structure, but none are recognized trending southward into the Arkoma Basin across the Cherokee Platform east of the Nemaha. It is presumed that incised channels extended around the southern end of the Nemaha Fault Zone and carried sediment into the Arkoma Basin from the west. Accordingly, lower Morrowan Cromwell Sandstone is thickest in the western part of the Arkoma Basin and thins to the east. The lack of sediment carried into the eastern part of the Arkoma Basin during the lower Morrowan resulted in a sand-starved depositional environment that was most favorable for limestone and shale deposition.

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Regional Overview of the Cromwell Play

INTRODUCTION

The Cromwell play occurs largely within the Arkoma Basin of southeastern Oklahoma but also extends westward into parts of structural provinces east and northeast of the Arbuckle Uplift. The play originally gained attention in the early 1900s because of prolific oil production from extremely porous, permeable, and shallowly buried sandstones near Ada. More recently, the Cromwell play is known as a major gas play with subordinate oil potential. Most, if not all, large fields have elements of structural entrapment, and purely stratigraphic traps are uncommon. Reservoir depth varies from a few thousand feet to >12,000 ft.

The goal of this study is to evaluate sandstone reservoirs in the Cromwell Member of the Union Valley Formation, define trapping mechanisms and reservoir properties, identify regional and local depositional trends, and clarify the stratigraphic nomenclature. Because of widespread changes in rock type and facies within the Cromwell and bounding formations, an effort was made to document them in order to understand regional correlations and utilize appropriate nomenclature. These goals were aided by field investigations conducted in conjunction with the Oklahoma Geological Survey (OGS) Cromwell field trip and guidebook of Suneson and Andrews (in press). The many references used to assist the fieldwork are included in the main reference list accompanying this report.

Another goal of this study was to correlate the subsurface Cromwell Sandstone to the surface Morrowan rocks that consist mostly of carbonates in the Ozark Uplift of northeast Oklahoma. This required construction of regional cross sections extending from sandstone outcrops near Ada, across the Arkoma Basin, and ending at measured sections near Ft. Gibson and Webbers Falls to the northeast. In addition, it was thought useful to relate the Morrowan and upper Springeran rocks of the Arkoma Basin to those in the Anadarko Basin. In regards to the OGS play-based workshop series, this study completes the evaluation of widespread Morrowan reservoirs in the State of Oklahoma (the Jackfork reservoir is very localized south of the Arkoma Basin).

Perception of the "Cromwell" as it is known today has not changed much since Rison and Bunn first referred to it in 1924 (Jordan, 1957). It consists of sandstone, shale, and limestone of extremely variable thickness and composition. The sandstone and reservoir were named for the Cromwell Oil and Gas Company, or for Joe Cromwell of the company in the discovery well in SW¼ sec. 15, T. 10 N., R. 8 E., near the town of Cromwell (Jordan, 1957). Exploratory drilling to the southwest of the discovery well made possible the correlation of this sandstone to outcrops southeast of Ada where Hollingsworth (1933) measured and described the type locality (secs. 29 and 30, T. 3 N., R. 7 E.).

Hollingsworth named the sandstone at the surface the "Union Valley Sandstone Member of the Wapanucka Formation" because it was prominently exposed along the flanks of a small valley just north of Frisco, a farming community about 8 mi southeast of Ada. It was in Frisco where local sweet potato farmers held union meetings (Withrow, 1968), hence the term "Union Valley" Sandstone. For several decades following, this terminology was preferred but also was used interchangeably with the name "Cromwell." Then in 1969, Withrow elevated the Union Valley to a formation name and defined the Cromwell Sandstone as a member. Since the late 1970s, the reservoir sandstone is usually referred to as the "Cromwell Sandstone," "Cromwell," or simply "Crom."

The early Cromwell play gained attention due to the discovery of large oil reserves at relatively shallow depths in structural traps along the western part of the Arkoma Basin. However, since the late 1960s, the Cromwell play has moved steadily eastward into deeper parts of the basin where gas is the primary hydrocarbon produced. Whereas much of Cromwell production in the western part of the play consists of both oil and gas at depths generally less than 3,000–4,000 ft, the eastern part of the play is almost entirely gas prone at depths reaching below 15,000 ft just north of the Choctaw Fault.

The Cromwell Sandstone in southeast Oklahoma is primarily a gas reservoir but also continues to yield significant amounts of oil. Figure 1 shows gas and oil production since 1919, when production records were first available for the Cromwell. Annual production is recorded for each year beginning in 1966 but is summarized as a single value for years between 1919 and 1965. This plot shows a maximum annual production rate of ~25 BCF and 983 MBO in 1991 to present-day rates of ~14 BCF and 500 MBO (IHS Energy). Annual gas production from the Cromwell has fallen almost 1 BCF each year over the past 10 years. Oil production similarly has fallen dramatically from almost 1 MMBO in 1992 to about half that through 2002. Cumulative production from just the Cromwell is ~120 MMBO and 835 BCF. Figure 2 shows gas and oil production during the same time period from wells having Cromwell production *commingled* with production from other reservoirs. Because of numerous stacked reservoirs in the Arkoma Basin, commingling is commonly practiced. A significant amount of the commingled production is probably attributed to the

Cromwell—perhaps 30–50% or more (gas) and 50% or more (oil). This would conservatively add an additional 20–30 MMBO and 30–40 BCF to the cumulative recovery from just the Cromwell. Annual production used to construct these graphs is given in Table 1. Currently, the highest volume Cromwell gas well is located in Kinta Field, SE¼SE¼NW¼ sec. 33, T. 8 N., R. 21 E. This well is operated by Texaco and is still active since completion in 1964. Cumulative production is >12.7 BCF. The highest volume oil well produced >5 MMBO since completion in 1928. That well is operated by Archibald and is located in Little River Field, NE¼ sec. 23, T. 7 N., R. 6 E., and is still active. Currently, there are 782 active wells producing from the Cromwell. A total of 2,198 producing wells have been recorded since discovery of this play (IHS Energy).

Most Cromwell fields are fully developed with the drilling of increased-density and location exception wells. Only a small percentage of fields appear to have any significant development potential remaining. A listing of Cromwell fields and cumulative production (all reservoirs) is given in Appendix 1.

The Cromwell was a common objective in the early history of the Arkoma Basin and some of the largest gas and oil fields were discovered in the three decades of the 1920s, '30s, and '40s. During that time, high-volume exploration and development wells were completed in both shallow and medium-depth Cromwell fields in: Cromwell (1922—oil), Seminole (1923—oil), Brooken (1925—gas), Bowlegs (1927—oil), Little River (1927—oil), Fitts (1933—oil+gas), Ashland South (1938—gas), Holdenville (1946—oil), and Cedars (1946). During the 1950s and '60s, large reserves were discovered in Wewoka District (1955—oil+gas), Pine Hollow South (1959—gas), Wilburton (1960—gas), Reams Northwest (1963—gas), and Peno (1965—gas). Exploration during the 1970s identified the well known Kinta (1976—gas) and Pittsburg (1979—gas) Fields.

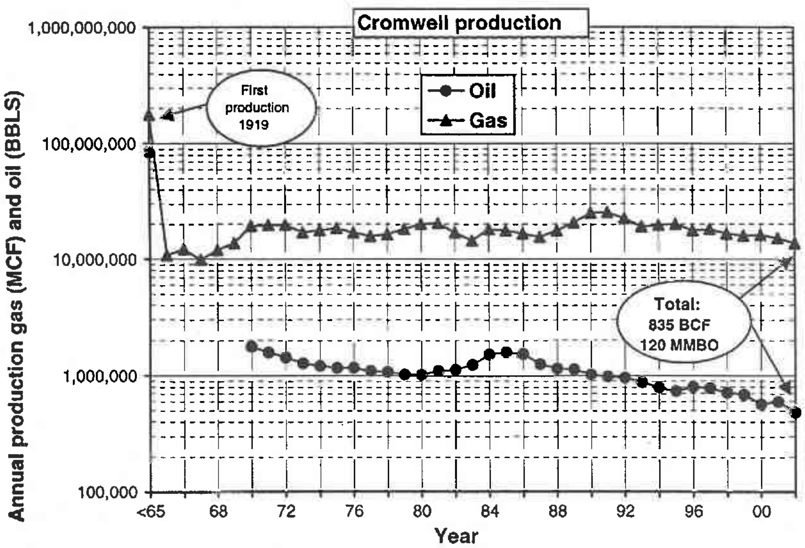


Figure 1. Annual gas and oil production curve from the Cromwell Sandstone. Data from IHS Energy, current through November 2002.

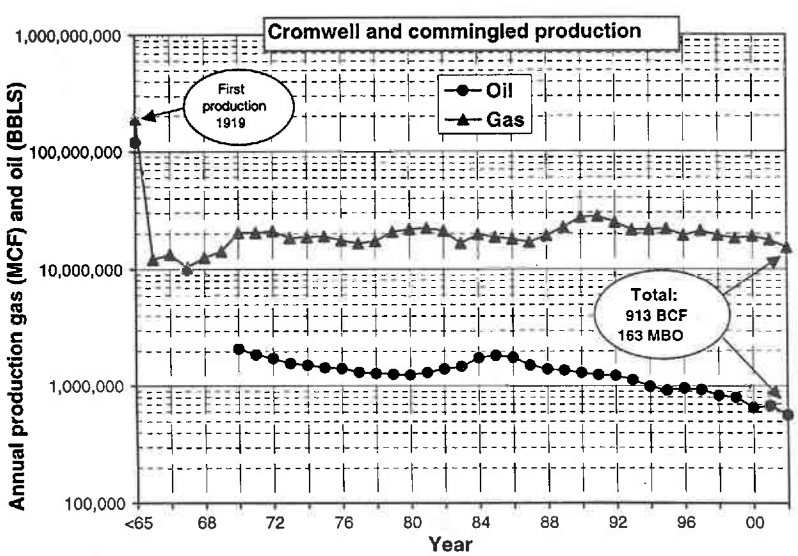


Figure 2. Annual gas and oil production curve from the Cromwell Sandstone, commingled with other reservoirs. Data from IHS Energy, current through November 2002.

The thickest Cromwell Sandstone and that which has the greatest porosity extends from outcrop near Ada northward through much of Seminole and western Okfuskee Counties. In these areas, the sandstone is commonly ~250 ft thick but thins to <100 ft several townships farther east and becomes increasingly calcareous. This change in thickness and composition persists to outcrop and in the shallow subsurface along the flanks of the Ozark Uplift where the lower Morrowan consists mostly of bioclastic limestone. Here, the amount of sandstone (Cromwell equivalent) is <50 ft thick. South of the trace of the Choctaw Fault, the Cromwell Sandstone is largely absent and replaced with marine shale.

Throughout the Arkoma Basin, the thickest accumulations of sandstone in both the Cromwell and Jefferson intervals are oriented north–south or northeast–southwest. Most commonly, these deposits occur in the form of bar ridges that are overlapping or adjacent to one another. Each succeeding sandstone "ridge" or group of "ridges" progressively thins to the east, away from outcrop. The principle sandstone accumulations were deposited in a very shallow, high energy, marine shelf environment and probably are not deltaic. Overall, deposition was relatively fast-paced causing bars to have unusual textural profiles characterized by relatively sharp lower contacts with shale. Bar margins and interbar facies have

TABLE 1. — Oil and Gas Production from the Cromwell Sandstone and Commingled Reservoirs

Cromwell only			Commingled			Cromwell plus Commingled		
Year	Oil (BBLS)	Gas (MCF)	Year	Oil (BBLS)	Gas (MCF)	Year	Oil (BBLS)	Gas (MCF)
<65	84,683,767	176,743,010	<65	35,590,588	13,218,177	<65	120,274,355	189,961,187
65		10,819,480	65		1,362,891	65	0	12,182,371
66		12,191,014	66		1,156,167	66	0	13,347,181
67		9,869,300	67		562,933	67	0	10,432,233
68		11,968,241	68		605,310	68	0	12,573,551
69		13,727,704	69		421,992	69	0	14,149,696
70	1,765,349	19,278,716	70	345,627	995,386	70	2,110,976	20,274,102
71	1,578,265	19,605,829	71	304,222	649,694	71	1,882,487	20,255,523
72	1,429,687	19,680,993	72	310,356	1,294,987	72	1,740,043	20,975,980
73	1,271,715	16,916,325	73	303,889	1,427,425	73	1,575,604	18,343,750
74	1,205,523	17,681,780	74	314,340	941,015	74	1,519,863	18,622,795
75	1,164,482	18,454,331	75	277,716	535,207	75	1,442,198	18,989,538
76	1,165,597	16,865,859	76	255,379	631,642	76	1,420,976	17,497,501
77	1,096,095	15,720,301	77	227,031	795,980	77	1,323,126	16,516,281
78	1,074,862	16,341,683	78	211,195	855,342	78	1,286,057	17,197,025
79	1,031,441	18,081,472	79	237,058	2,483,121	79	1,268,499	20,564,593
80	1,028,637	20,008,293	80	219,457	1,683,093	80	1,248,094	21,691,386
81	1,110,603	20,280,531	81	201,121	1,887,550	81	1,311,724	22,168,081
82	1,130,564	16,851,838	82	279,308	4,209,599	82	1,409,872	21,061,437
83	1,245,310	14,379,859	83	241,287	2,202,130	83	1,486,597	16,581,989
84	1,526,354	17,978,638	84	230,385	1,662,846	84	1,756,739	19,641,484
85	1,593,347	17,530,726	85	247,853	1,139,299	85	1,841,200	18,670,025
86	1,526,165	16,492,482	86	243,095	1,489,308	86	1,769,260	17,981,790
87	1,245,936	15,428,246	87	267,331	1,459,393	87	1,513,267	16,887,639
88	1,147,491	17,530,625	88	256,761	1,703,764	88	1,404,252	19,234,389
89	1,126,093	20,584,083	89	245,730	2,038,485	89	1,371,823	22,622,568
90	1,018,388	24,967,983	90	286,808	2,325,104	90	1,305,196	27,293,087
91	983,401	25,260,681	91	265,416	2,503,302	91	1,248,817	27,763,983
92	957,072	22,382,289	92	275,591	2,349,822	92	1,232,663	24,732,111
93	887,751	19,050,811	93	245,405	2,375,976	93	1,133,156	21,426,787
94	795,916	19,600,318	94	196,972	1,999,340	94	992,888	21,599,658
95	733,976	19,979,139	95	186,963	1,889,286	95	920,939	21,868,425
96	798,002	17,596,270	96	165,575	1,654,787	96	963,577	19,251,057
97	780,318	18,058,775	97	149,605	3,013,778	97	929,923	21,072,553
98	711,000	16,523,989	98	122,073	2,808,759	98	833,073	19,332,748
99	683,833	15,911,568	99	121,031	2,410,758	99	804,864	18,322,326
00	566,302	16,109,180	00	90,529	2,843,536	00	656,831	18,952,716
01	591,877	15,170,482	01	83,155	2,475,267	01	675,032	17,645,749
02	482,686	13,720,998	02	76,500	1,571,123	02	559,186	15,292,121
Cumulative production	**120,137,805**	**835,343,842**		**43,075,352**	**77,633,574**		**163,213,157**	**912,977,416**

Data from IHS Energy, current through November 2002.

various degrees of coarsening-upward textural profiles typical of such deposits. No distinct channel or incised channel facies were identified in either the subsurface or the outcrops near Ada. However, small tidal channels are interpreted at outcrop near Webbers Falls in eastern Oklahoma. This facies has distinct down-cutting and consists of moderately cross-bedded crinoidal packstone and grainstone.

CROMWELL (MORROW)–SPRINGER BOUNDARY AND CLAY MINERALOGY OF SHALE

This discussion is included to comment on similarities in log characteristics between the Cromwell–Jefferson contact in the Arkoma Basin and the Morrow–Springer contact in the Anadarko Basin (Fig. 3). It seems likely that similar depositional episodes took place on a large regional scale beyond the borders of present-day basins in Oklahoma. The Morrow–Springer contact in both basins is usually picked on logs where a sharp *increase* in conductivity (a sharp *decrease* in resistivity) is evident at the top of the Springer shale. That log pick is commonly used to represent the Mississippian–Pennsylvanian boundary in the subsurface. As noted in the Springer Gas Play publication of Andrews (2001), however, the actual system boundary is more likely *below* the log pick that separates the lithostratigraphic Cromwell from the Jefferson (or Morrow and Springer units in the Anadarko Basin). The actual systemic boundary is probably below the Jefferson sandstone of this report as noted on Figure 6. In the Arkoma Basin, the presumed Mississippian–Pennsylvanian boundary is probably represented by a discrete, unconformable contact rather than being gradational, as it is in the southern part of the Anadarko Basin.

The following discussion appears in Andrews' publication (2001) and is relevant to this play. In 1958, Weaver studied clay mineralogy of the Morrow and Springer intervals in the Ardmore, Anadarko, and Arkoma Basins of Oklahoma. He discovered major differences in clay content between the Morrow and Springer lithostratigraphic units. Morrow (Cromwell in the Arkoma Basin) shale is characterized by a high percentage of illite and "varying amounts of chlorite, kaolinite, and mixed-layer illite-montmorillonite and/or montmorillonite" (Weaver,

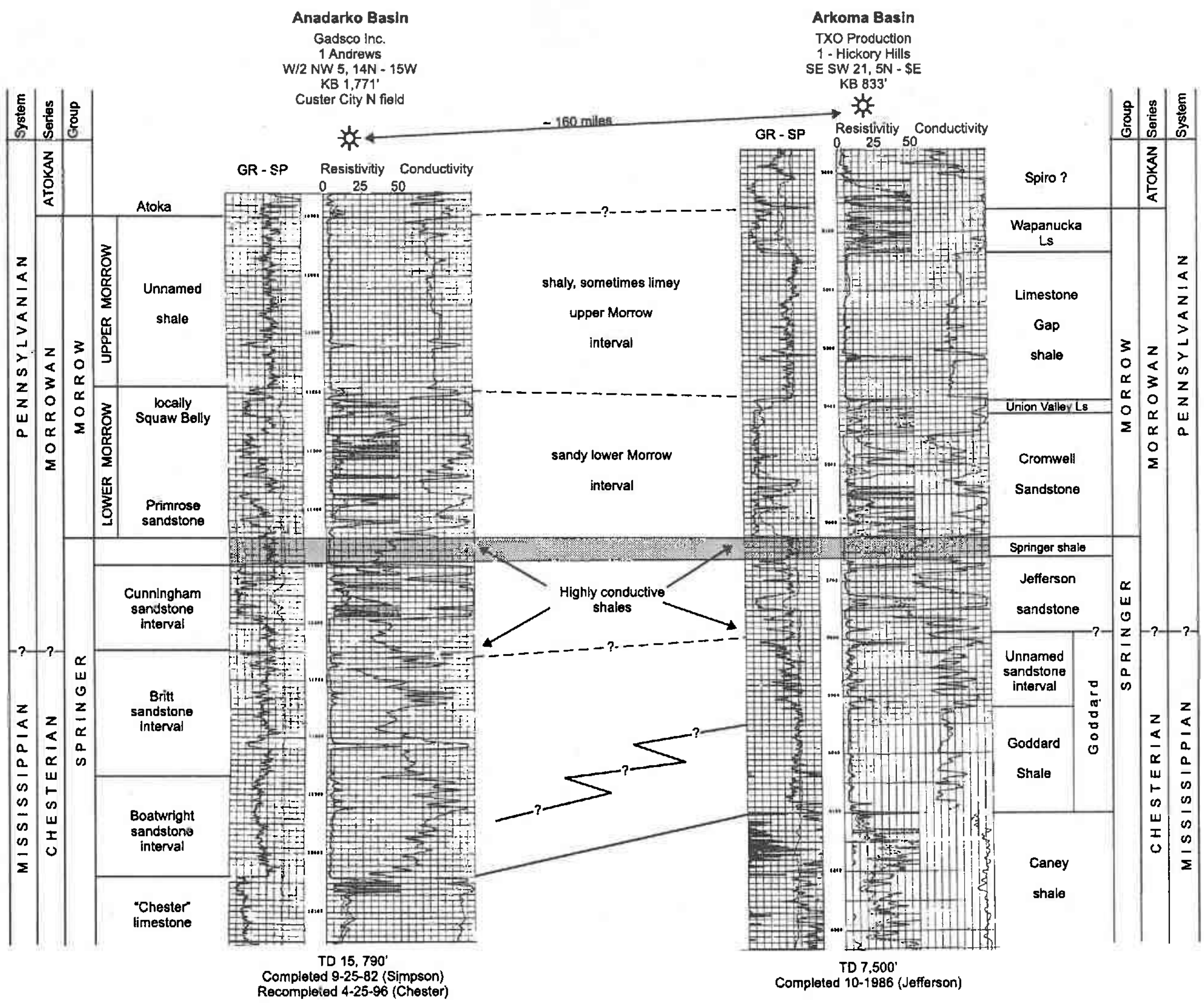


Figure 3. Comparison of Morrowan stratigraphy between the Arkoma Basin of southeastern Oklahoma and the Anadarko Basin of southwestern Oklahoma.

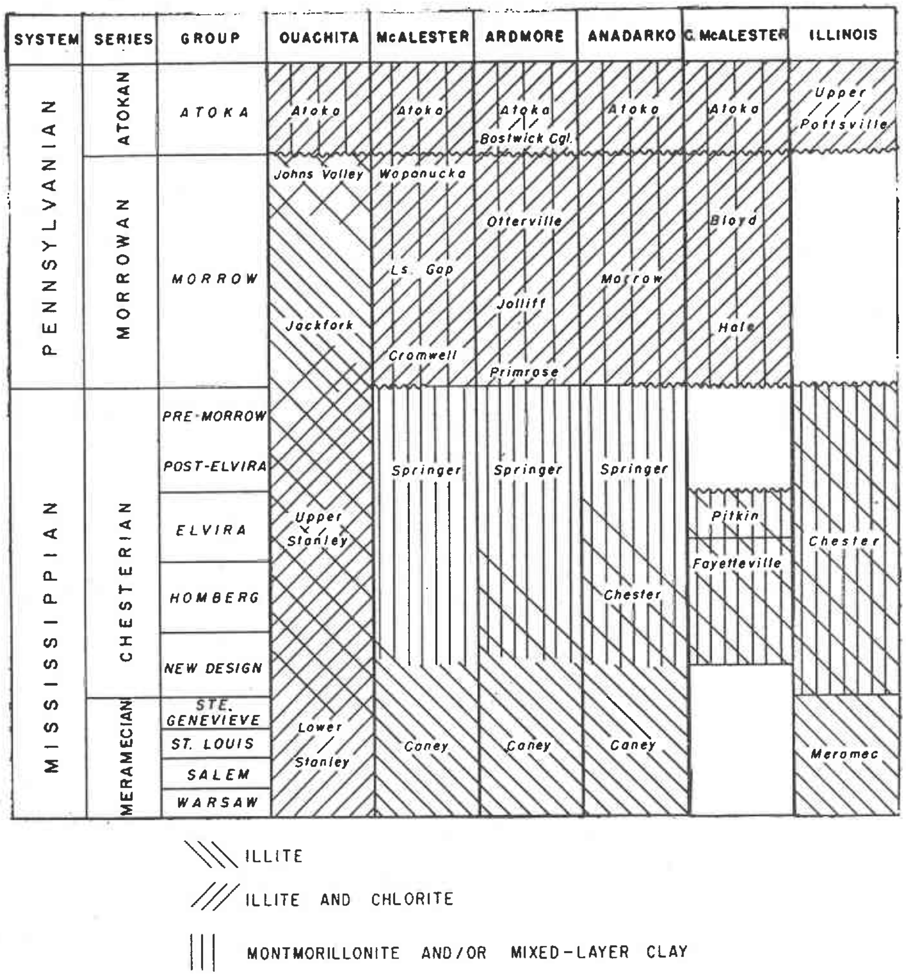


Figure 4. Correlation chart of Upper Mississippian and Lower Pennsylvanian rocks based on clay mineralogy. From Weaver (1958, fig. 2).

1958, p. 289). Springer shales, on the other hand, are "characterized by the abundance of montmorillonite and mixed-layer illite-chlorite-montmorillonite, and the *lack* of illite" (p. 283). A comparison of clay mineralogies for these two groups is shown in the correlation chart of Figure 4. The typical X-ray patterns of Morrow and Springer (Chester) clays are shown in Figure 5. Note the similarities in clay content of shale between the Anadarko and McAlester (Arkoma) Basins for both the Atoka and Morrow. Then note the differences in both basins between the Morrow and Springer/Chester shales. These clay differences are probably responsible for the different responses observed on resistivity well logs through this interval.

STRATIGRAPHY

Arkoma Basin, Ada High, Frank's Graben, and Lawrence Horst Provinces

The Cromwell Sandstone is lower Pennsylvanian in age. It overlies a thinner sandstone sequence informally called the Jefferson sandstone—the interval of which is considered "lower Cromwell" by some geologists and probably also lower Pennsylvanian in age. Because the Cromwell Sandstone was extensively studied at outcrop and is correlative to nearby subsurface sandstone sequences in well logs, formal terminology of the Cromwell is established in the western part of the study area (see Withrow, 1969). In his report, Withrow identified the Cromwell Sandstone as a lower Member of the Union Valley Formation, the upper Member being the Union Valley Limestone (Fig. 6). The Cromwell is further subdivided into upper and lower sub-members, but this division is hard to apply consistently over large areas so it is applied informally in this report. The Union Valley Limestone overlies the Cromwell except where it is absent due to erosion, non-deposition, or faulting. Its thickness and composition are highly variable. The contact between the Union Valley Limestone and Cromwell Sandstone is often difficult to pick on well logs because of the gradational boundary—either the Cromwell becomes limy toward the top or the Union Valley Limestone becomes sandy at its base.

Based on compelling lithostratigraphic relationships within the lower Morrowan, the Union Valley Limestone appears to be correlative with the Brewer Bend Limestone of the Ozark uplift. However, biostratigraphic correlations based on conodont assemblages (Grayson, 1990) indicate that the Union Valley Limestone is slightly older than the Brewer Bend Limestone and may be correlative to a particular limestone bed or limestone sequence in the upper part of the Braggs Member. In particular, the lowest occurrence of *Indiognathodus sinuosis* is found in the very upper part of the Braggs Member (Ozark Uplift) and *below* the Brewer Bend Limestone. The lowest occurrence of this same conodont is found immediately *above* the Union Valley Limestone at Canyon Creek near Ada. This being the case, the Brewer Bend Limestone is interpreted to grade into shale west of outcrop and is equivalent to the lower part of the Wapanucka Formation. These biostratigraphic correlations are based solely on very limited conodont recoveries and should be considered tentative.

The lower contact of the Cromwell is unconformable on a variety of rock units. In structural provinces east of the Arbuckle Uplift, the Cromwell is underlain successively by the Springer shale, Jefferson sandstone, Goddard shale, "False" Caney, and Caney. Farther east, the Springer shale becomes indistinct and the Jefferson sandstone and Goddard shale become discontinuous. In the Ozark Uplift area of northeast Oklahoma, the Cromwell or equivalents normally overlie the Pitkin Limestone

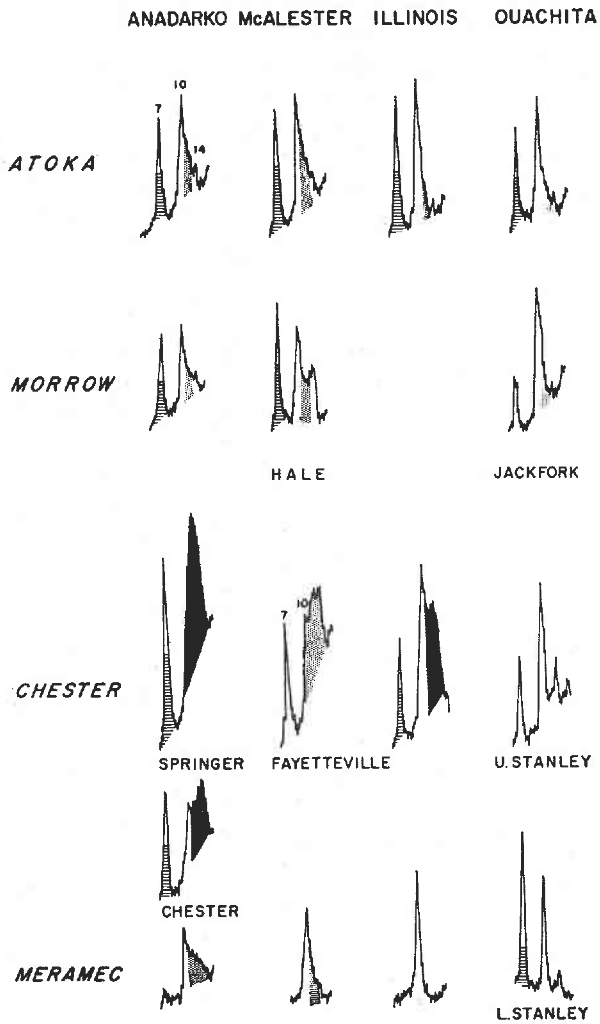


Figure 5. Typical X-ray diffraction patterns of Upper Mississippian and Lower Pennsylvanian shales. Stippled—mixed-layer illite-montmorillonite; solid—montmorillonite; horizontal-lined—kaolinite; open 10A—illite; open 7A and 14 A—chlorite. From Weaver (1958, fig. 3).

(equivalent to the "False" Caney) except where it is eroded. This relationship occurs just north of Cookson on Elk Creek (east of Lake Tenkiller) where the lower Morrowan (Cromwell equivalent) unconformably rests on Fayetteville Shale (Caney equivalent). At this location the Fayetteville Shale (Fig. 7) is partially eroded and the unconformable surface contains large fragments of the eroded Pitkin Limestone (Fig. 8). These relationships are shown in the stratigraphic chart of Figure 6.

The Cromwell of the Arkoma Basin is equivalent to the lower part of the Morrowan in the Ozark Uplift of Oklahoma and Arkansas. The big difference, of course, is that the Cromwell is mostly sandstone, whereas the exposed Morrow is mostly limestone with subordinate sandstone. The stratigraphic relationship between the Cromwell and the Morrowan is shown in Figure 6. Although terminology between the surface and the subsurface units is confusing, the correlation chart shows that the Cromwell Sandstone in the Arkoma Basin is equivalent to limestone beds of the Braggs Member in the lower part of the Sausbee Formation in the Ozark Uplift. In Arkansas, the Prairie Grove Member of the Hale Formation is equivalent to the Cromwell.

Today, Cromwell terminology is pretty "clean," meaning that there are only a few acceptable subsurface names used in its place. Historically, however, there have been other informal subsurface names used as shown in Figure 6.

In the subsurface, Cromwell Sandstone exceeds 250 ft in thickness, particularly in a north–south belt extending through much of Ts. 3–5 N., R. 9 E. (~10 mi east-northeast of outcrop). This compares to the sandstone thickness of 240 ft measured by Hollingsworth (1933). Farther to the northeast, the Cromwell Sandstone exceeds 100 ft in several north–south belts, each a few miles wide. East of R. 18 E., the thickness of Cromwell Sandstone seldom exceeds 100 ft. Approaching the Ozark Uplift to the northeast, the Cromwell (or equivalent) thins and becomes increasingly limy until it is eventually dominated by packstone and grainstone (fossiliferous limestone) at outcrop. There is little Cromwell Sandstone north of Ts. 12–13 N., whereas the overlying Union Valley Limestone thickens to more than 50–100 ft in that area. In a basinward direction to the south, the Cromwell Sandstone is generally thin or absent south of the trace of the Choctaw Fault. These characteristics are shown on the regional sandstone map of Plate 1.

In addition to well-log characteristics, certain regionally persistent stratigraphic marker beds are useful in correlating the Cromwell of the Arkoma Basin with the lower Morrow of the Anadarko Basin (Fig. 3). Specifically, the upper Cromwell appears to be stratigraphically equivalent to the upper part of the lower Morrow in the Anadarko Basin, and the lower part of the Cromwell appears to be stratigraphically equivalent to the Primrose sandstone. In fact, the entire Union Valley Formation has similarities to the Morrow in the Anadarko Basin: the Cromwell is overlain by inconsistent accumulations of limestone of the Union Valley Limestone Member in a manner similar to the Squaw Belly overlying the lower Morrow in the Anadarko Basin. Furthermore, the Jefferson sandstone appears to correlate to the Cunningham sandstone of the Anadarko Basin and the low resistivity (high conductivity) shale separating the Jefferson from the Cromwell has a log character similar to that of the low resistivity shale separating the Morrow and Springer–Cunningham in the Anadarko Basin. The thickness of that shale, however, is much greater in the Anadarko Basin.

The Morrowan in the Ozark Uplift

Trending to the northeast from the Arkoma Basin, the Cromwell interval thins and changes facies and composition from sandstone, to mostly shale, and then to fossiliferous limestone. These changes occur rapidly in the very shallow subsurface adjacent to the Ozark Uplift and persist to outcrop in northeastern Oklahoma. In this region, formal surface terminology of the Morrowan is more applicable because the section consists mostly of limestone and the Cromwell Sandstone is absent. The Braggs Mem-

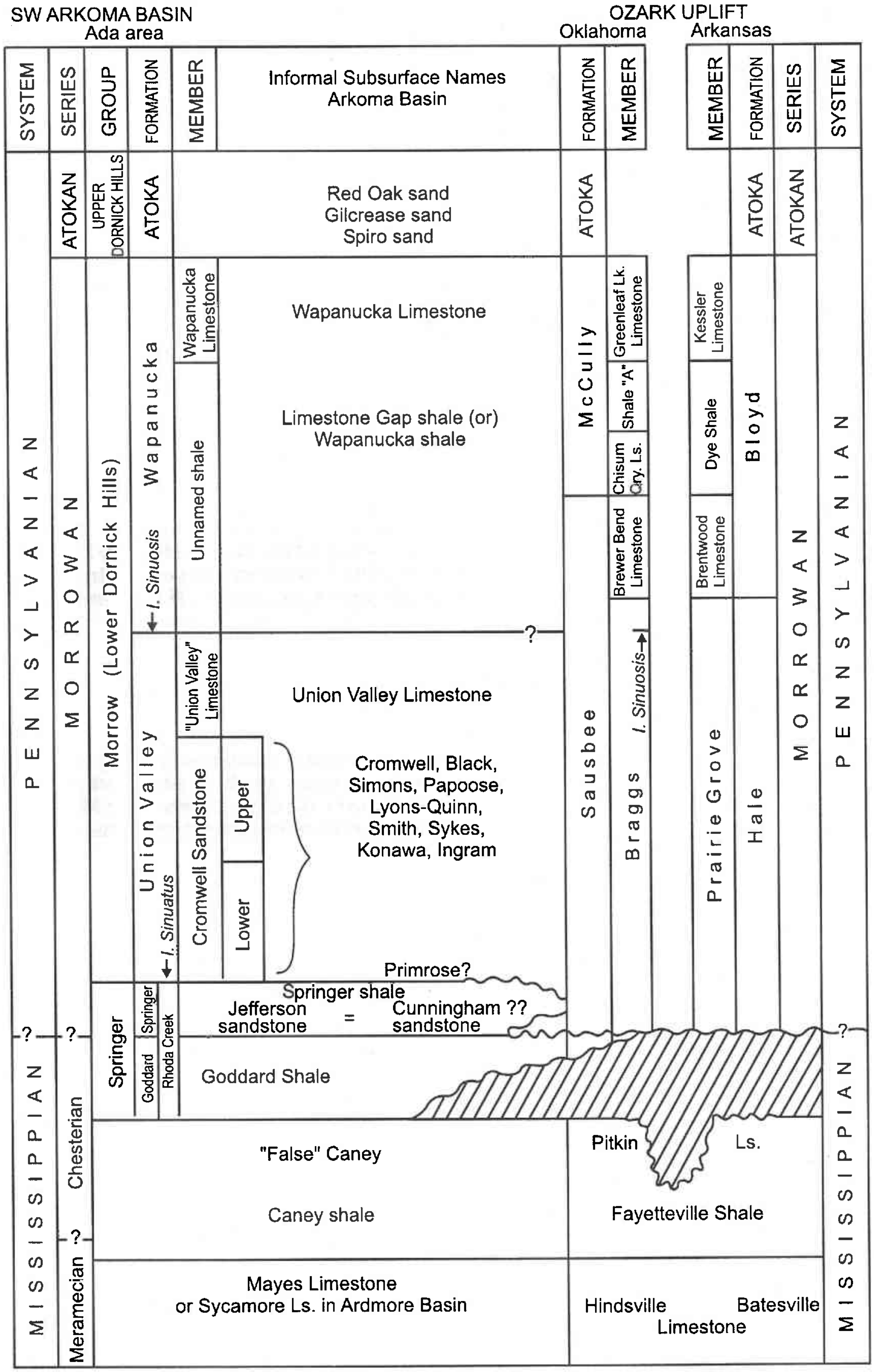


Figure 6. Stratigraphic chart of the Morrowan Series in the Arkoma Basin. Modified from Andrews (2001), Blackwood (1999), Branson (1959), Field (1987), Grayson (1990), Stout (1991), Sutherland (1988), and Withrow (1969).

Figure 7. Possible contact of the Morrow Sandstone (Sausbee Formation) overlying Fayetteville Shale (Caney), where Elk Creek crosses Hwy. 82 near Cookson, Oklahoma.

Figure 8. Pebble- and cobble-size clasts of Pitkin Limestone comprising conglomerate at unconformable contact of Figure 7 (above).

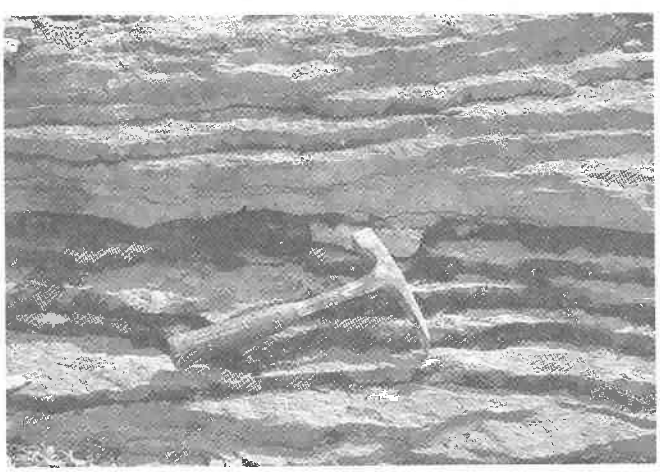


Figure 9. Ripple-bedded sandstone of the Morrow (Sausbee Formation) at Elk Creek.

ber of the Sausbee Formation is largely equivalent to the Cromwell interval and excellent outcrops of this unit occur at Braggs Mountain, Webbers Falls, and near Cookson on Elk Creek. These sections are described by Sutherland (1979) and are included in the Cromwell companion field-trip guidebook of Suneson and Andrews (in press). Incomplete sections of the Braggs Member are <100 ft thick at the later two locations, whereas it is only about 55 ft thick at Braggs Mountain. The maximum thickness of the Braggs Member is probably <150 ft, which is comparable to that interpreted from subsurface logs in nearby wells. Minor sandstone occurs locally in the lowest part of the Braggs Member and is correlative to the Jefferson sandstone interval.

Sandstone

Morrowan sandstone in the Ozark Uplift consists mostly of fine quartz grains, and cementation and sedimentary structures vary greatly from area to area. North of Cookson on Elk Creek (east of Lake Tenkiller), the sandstone is ~40 ft thick, is light colored (light gray to dirty white), and is well bedded in layers generally less than an inch or two thick. Ripple bedding (Fig. 9) and small to medium-scale cross bedding (Fig. 10) are common. Silica cementation predominates causing low permeability. Some bedding surfaces appear to be scoured by storm? currents, and horizontal trace fossils and carbonized plant debris are locally found on bedding surfaces. The latter is indicative of terrestrial proximity (to the northeast).

Sandstone in the Braggs Mountain section north of Webbers Falls (west of Lake Tenkiller and Greenleaf Reservoir) is ~14 ft thick and is very different from sandstone exposed on Elk Creek. The sandstone at Braggs Mountain is normally tightly cemented with calcite (rather than silica) and is medium gray in color making distinction between it and the underlying Pitkin Limestone difficult (Fig. 11A). The matrix calcite probably originates from diagenetic alteration of minute crinoidal fragments.

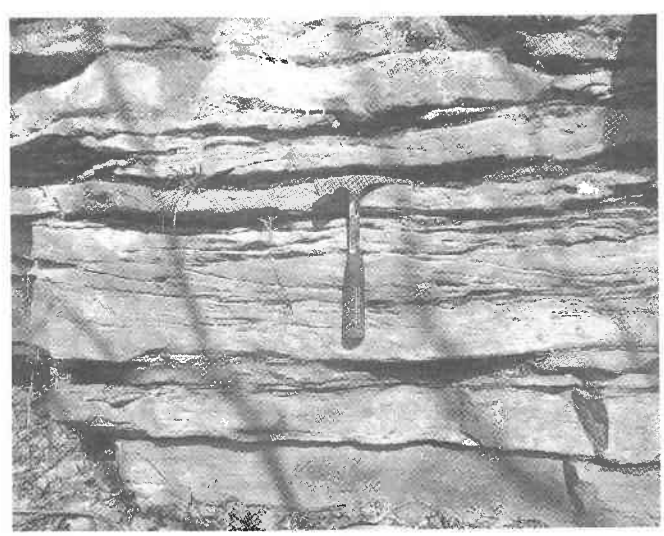


Figure 10. Low-angle cross bedding and ripple bedding in the Morrow Sandstone (Sausbee Formation) at Elk Creek.

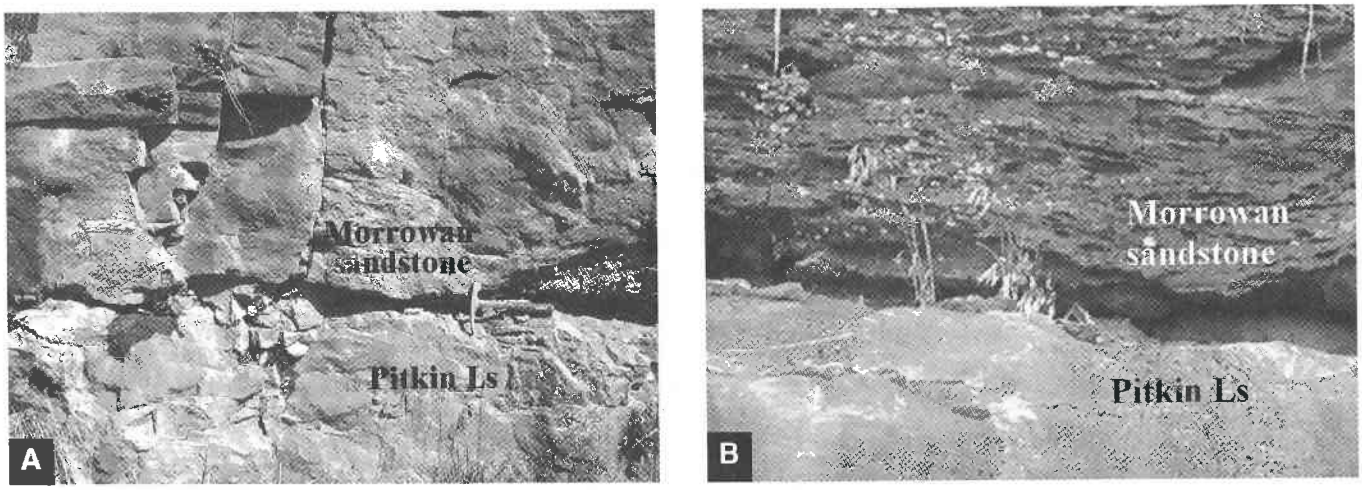


Figure 11. *A*—Pennsylvanian/Mississippian contact at the Braggs Mountain measured section south of Hwy. 62 on Hwy. 10. The contact occurs between basal sandstone in the lower Morrowan Braggs Member (above rock hammer) and the underlying Pitkin Limestone (below rock hammer). *B*—Same contact showing cross bedding in the weathered sandstone overlying the Pitkin Limestone. Note the undulatory surface atop of the Mississippian Pitkin Limestone.

Where this type of cementation prevails, the sandstone is very hard and durable, bedding is poorly defined, and vertical fractures are conspicuous (Fig. 11A). This sandstone horizon also contains zones that are more poorly cemented resulting in erosional cavities in the outcrop. In other places, the sandstone contains selective cementation along certain bedding surfaces. Upon weathering, a textural profile develops that accentuates original cross bedding in the sandstone (Fig. 11B). Note inclination of bedding to the right (south-basinward).

Limestone

Morrowan-age rocks in the Ozark Uplift are chiefly limestone that are locally interbedded with shale and sandstone. The limestone is almost always bioclastic in texture and composition, although very minor amounts of micrite and finely crystalline varieties are recognized locally. The overwhelming majority of limestone is classified as packstone with lesser amounts of grainstone and wackestone assemblages. The limestone contains abundant invertebrate fossil fragments, chiefly crinoids (Fig. 12), brachiopods (Fig. 13), and bryozoans. Marine trace fossils are less common but occasionally found on bedding surfaces (Fig. 14). Little or no porosity was noted in these rocks and their potential as reservoirs is doubtful.

Morrowan carbonates look very much like typical detrital rocks and have many of the same sedimentary structures. Bedding is usually wavy and locally resembles ripple bedding (Fig. 15). Small- and large-scale cross bedding is very common (Fig. 16) and sequences of like-textured limestone form discrete units (Fig. 17). The lowermost unit at Webbers Falls lock and dam shows distinct

Figure 12. Crinoidal wackestone/packstone in the Braggs Member of the Sausbee Formation at Webbers Falls lock and dam (lower Morrowan).

Figure 13. Bivalve shells and crinoid stems in the Braggs Member of the Sausbee Formation at Webbers Falls lock and dam (lower Morrowan).

Figure 14. Horizontal trace fossils in the Braggs Member of the Sausbee Formation at Webbers Falls lock and dam (lower Morrowan).

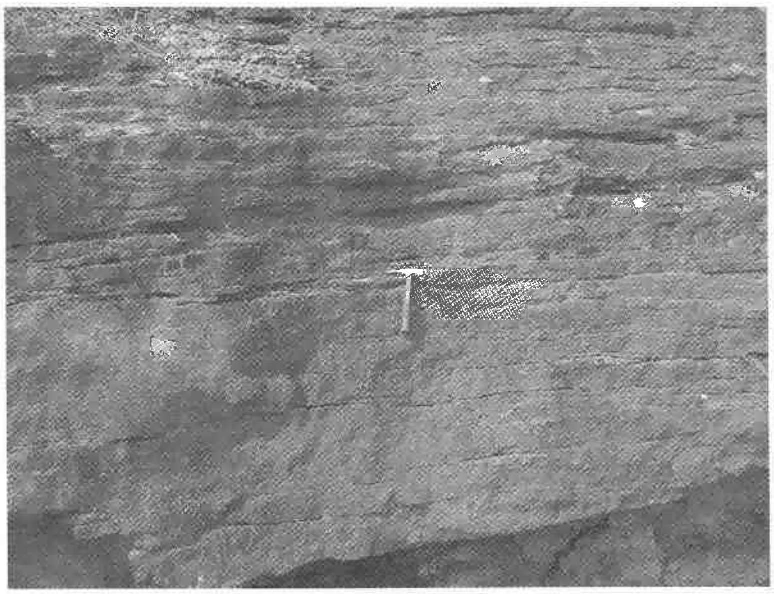


Figure 15. Horizontal and irregular bedding of wackestone/packstone in the Braggs Member of the Sausbee Formation at Webbers Falls lock and dam (lower Morrowan).

Figure 16. Low-angle cross bedding of wackestone/packstone in the Braggs Member of the Sausbee Formation at Webbers Falls lock and dam (lower Morrowan).

Figure 17. Discrete bed sets of alternating limestone (wackestone/packstone) and shale in the Sausbee Formation at Webbers Falls lock and dam (lower Morrowan). The rounded upper unit consists of bioherm accumulations.

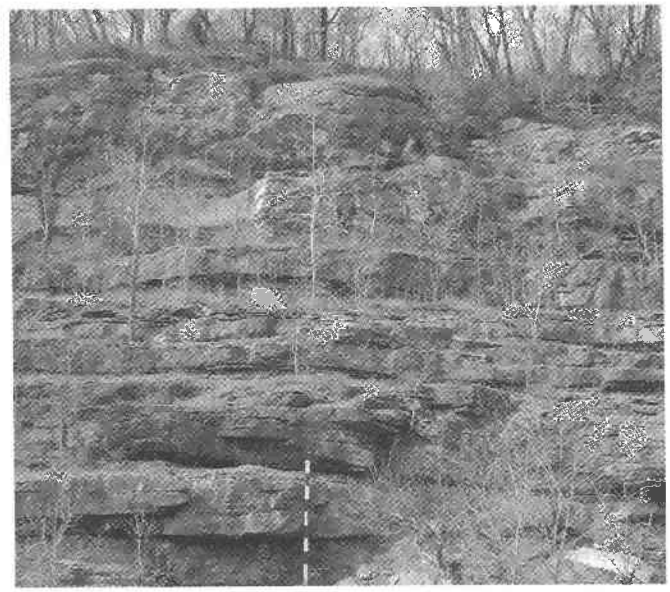


Figure 18. Down-cutting possibly as a result of tidal channeling in the Braggs Member of the Sausbee Formation at Webbers Falls lock and dam (lower Morrowan).

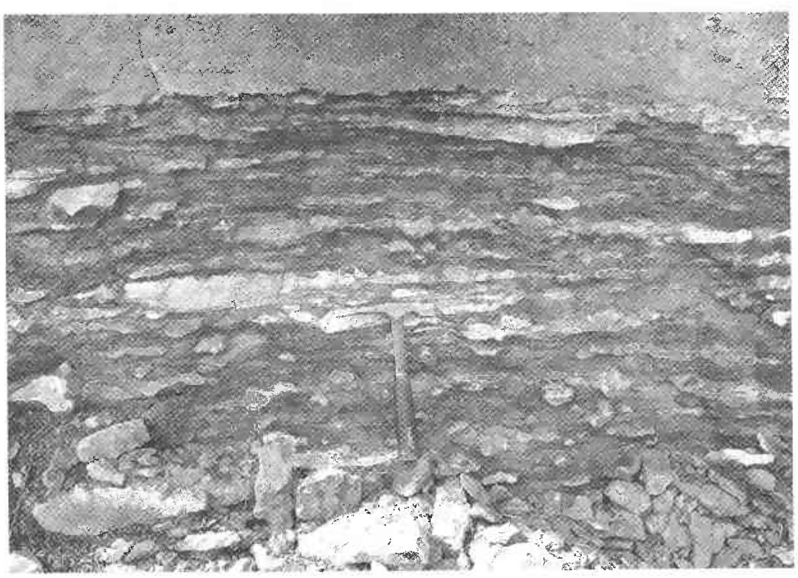


Figure 19. Lenticular bedding laterally adjacent to tidal channel of Figure 18.

Figure 20. Biohermal mounds at the top of a cliff at Webbers Falls lock and dam (see Fig. 17).

down cutting (Fig. 18), which may indicate tidal channeling. Other depositional features resemble lenticular or flaser bedding (Fig. 19) that characterizes tidal flat deposits. Additionally, the uppermost carbonate unit on the cliff face at Webbers Falls appears as large, rounded mounds (Fig. 20) that are interpreted to be bioherms.

DISCUSSION OF CROMWELL SANDSTONE IN THE ARKOMA BASIN, INCLUDING PETROLOGY

The Cromwell Sandstone is locally one of the best reservoirs in Oklahoma with very high porosity and permeability. At outcrop or in the subsurface, the thickest-bedded sandstone is dirty white to light gray in color and generally moderately well sorted with subangular fine quartz grains. Porosity and permeability may be so exceptional that a person can exhale directly into the sample. Typically, porosity is extremely variable both at outcrop and in the subsurface. Well logs show porosity varying from only a few percent to >20% even in the same well, but it is usually in the range of 6–14%. Because of exceptional permeability and lack of intergranular cement, outcrops near Ada are very poorly consolidated and often have iron staining (Fig. 21). This results in poor exposures and scarcity of sedimentary structures that would otherwise be important for the interpretation of facies and depositional environments. The better exposures near Ada that were described in earlier published studies are for the most part covered by railroad/highway reclamation. The lowermost sandstone beds near Ada contain abundant marine trace fossils, hydrocarbon odors, and apparent oil staining.

Using a hand lens, the Cromwell appears to be composed almost entirely of quartz grains with minor amounts of rock fragments or other dark impurities. Stout (1991) determined the sandstone to range from quartz arenite to quartz wacke (a sandstone having >10 matrix clay). Sutherland (1988) determined the Cromwell to be primarily a quartz arenite. Stout also reported glauconite as a significant detrital constituent with subordinate amounts of zircon, tourmaline, rutile, leucoxene, plagioclase, chert, muscovite, and biotite. According to Stout, the detrital matrix consists of clay with smaller amounts of silty material. The clays are primarily illitic with some recrystalization to chorite. The most common authigenic clays in the sandstone are chlorite, illite, and kaolinite (Stout, 1991).

Cementation consists of silica (usually overgrowths) or calcite and/or dolomite. In core samples, lighter coloring and lack of hydrocarbon staining is often the result of carbonate cementation (see core photograph above and below the depth of 2,734 ft in the Sunray well, Appendix 5), whereas silica cementation usually does not have this color contrast. Fragments of invertebrates (see photographs of two cores from the Sunray well, Appendix 5) often dominate certain sandstone layers and these layers always contain carbonate cement as a diagenetic alteration of the fossil fragments. Carbonate cement is obviously more prevalent to the northeast as the sandstone grades into limestone.

CORE DATA

Core data from eight wells are summarized in Table 2. Three of the wells cored multiple intervals in the Cromwell Sandstone, and where this occurs, dashed lines are used to distinguish individual core intervals. Deep Rock Oil Company drilled all of the wells in the 1940s; so the wells lack porosity logs. However, some of the wells were recently "twined," and the acquisition of modern density-

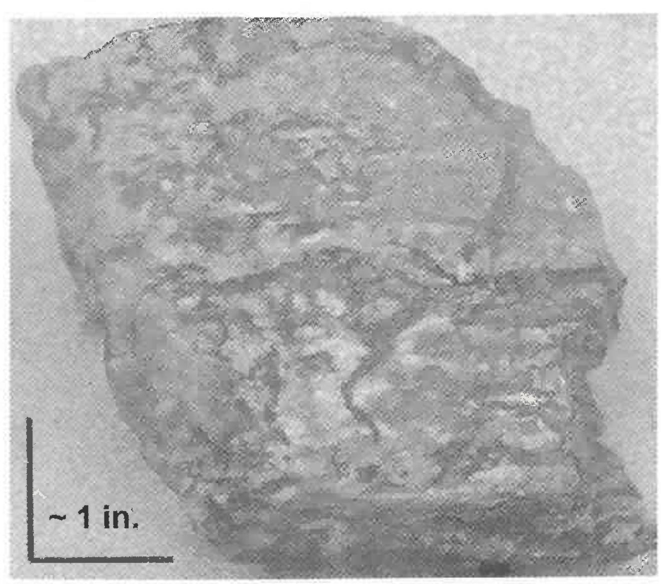


Figure 21. Weathered Cromwell Sandstone showing iron staining. The sandstone is poorly cemented and has extremely high porosity and permeability. Outcrop occurs in a stream cut-bank south of Ada.

TABLE 2. — Cromwell Core Data from Eight Wells Drilled by Deep Rock Oil Company

Fixico #1 — Nw Ne Sw 1, 6N-10E

Depth	Porosity	Permeability
4,439	7	0.2
4,441	9.8	0.5
4,445	6.3	0.4
4,445	7	0.2
4,447	9.7	0.7
4,448	6.3	1
4,448	17.9	40
4,449	14.2	20
4,449	14.5	25
4,450	14.1	18
4,451	13.8	19
4,451	4.8	0.1
4,452	5.1	0.5
4,454	6.3	0.6
4,472	6.2	0.4
4,472	1.5	0.5
4,473	7	4.2
4,473	15.9	25
4,474	10.4	14
4,474	16.6	24
4,475	14.8	38
4,476	11.3	8.4
4,476	0.7	0.7
4,476	6.1	0.2
4,477	6.5	0.7
4,478	3.7	0.7
4,478	2.7	0.7
4,479	3.3	0.7
4,480	3.7	1
4,480	7.1	0.7
4,485	8.2	4.4
4,486	13.6	30
4,487	13.6	36
4,488	10.6	11
4,489	12.3	17

Troup-Moore #1 — Nw Nw Se 11, 6N-10E

Depth	Porosity	Permeability
4,484	6.7	0.01
4,485	5.8	0.01
4,485	9.4	3.2
4,486	7.9	0.7
4,486	15.2	321
4,487	13	13
4,487	7.7	0.6
4,488	9.1	1.5
4,488	11.7	11
4,489	15.5	178
4,489	14.8	117
4,490	14.8	131
4,518	4.6	0.2
4,522	6.9	0.3
4,523	9.3	52
4,524	11.9	56
4,525	9.7	18
4,526	14.4	326
4,527	17.3	230

Myers #1 — Se Ne 7, 7N-10E

Depth	Porosity	Permeability
3,551	17.9	145
3,552	17.1	60
3,553	13	9.3
3,554	10.5	4.4
3,570	9.1	0.1
3,571	9.9	0.2
3,572	9.3	0.2
3,572	8.1	0.1
3,573	5.8	0.1
3,574	6.9	0.1
3,575	7.6	6.5
3,576	14.2	90
3,577	14.6	138
3,578	5	0.15
3,587	12.8	196
3,588	14.5	117
3,589	14.8	253
3,590	14.9	414

Myers #2 — Se Ne Ne 7, 7N-10E

Depth	Porosity	Permeability
3,577	14.9	223
3,578	14.9	312
3,579	15.8	349
3,580	14.3	175
3,581	15.8	270

Myers #4 — Nw Se Ne 7, 7N-10E

Depth	Porosity	Permeability
3,580	14.2	283
3,581	9.6	28
3,582	8.1	4.3
3,584	6.2	0.4
3,587	14.9	213
3,588	13.4	426
3,589	5.6	1.4

Price-Boyd #1 — Se Nw Sw 21, 7N-10E

Depth	Porosity	Permeability
3,913	4.2	0.1
3,914	15.3	129
3,916	13.1	83
3,920	16.1	254
3,921	15.5	266
3,923	15.5	310
3,923	13	66
3,924	12.4	77
3,925	14.1	205
3,926	15.1	216
3,927	15.3	262
3,930	15.7	131

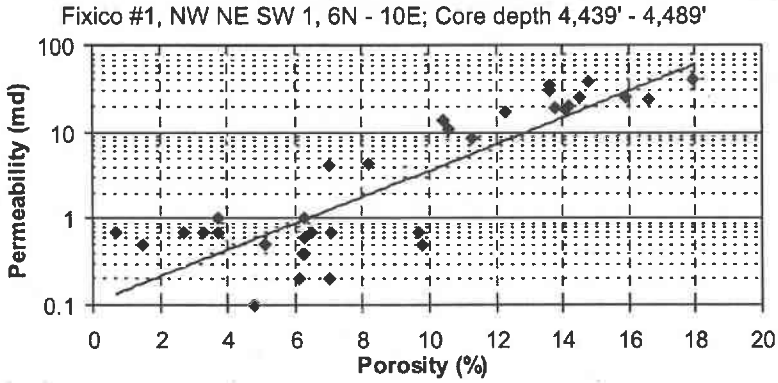
Mealy-Price Community #1 — Ne Ne Sw 21, 7N-10E

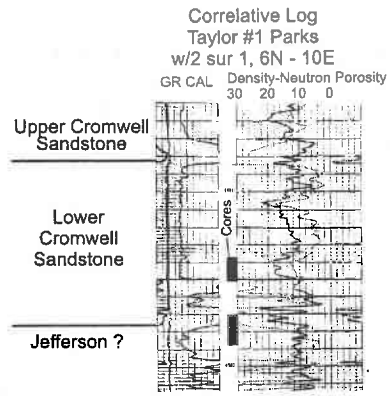
Depth	Porosity	Permeability
3,925	15.3	315
3,926	5.8	0.4
3,927	15.7	287
3,928	3.9	0.1
3,929	2.3	0.1
3,930	13.7	153
3,931	14.9	349

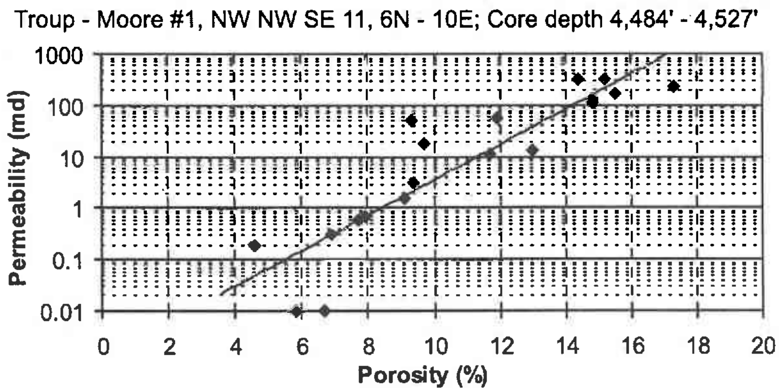
Flinchum #1 — Ne Ne 21, 7N-10E

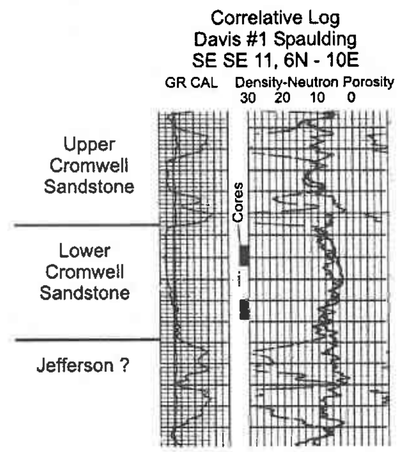
Depth	Porosity	Permeability
3,959	9.1	14.0
3,963	10.5	16.0
3,964	10.2	5.5
3,966	11.1	8.2
3,969	6.8	0.7
3,970	6.8	0.6
3,971	8.2	2.8
3,972	9.1	2.4
3,973	8.7	0.9
3,975	8.8	1.3
3,977	7.9	0.5
3,978	7.6	1.2

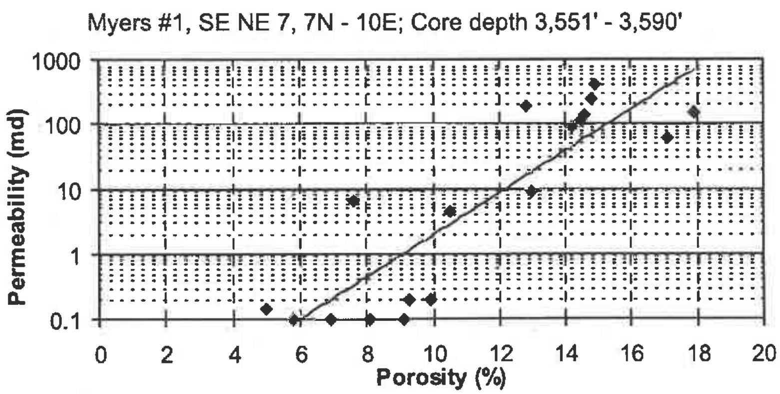
Dashed lines indicate breaks in cored interval.

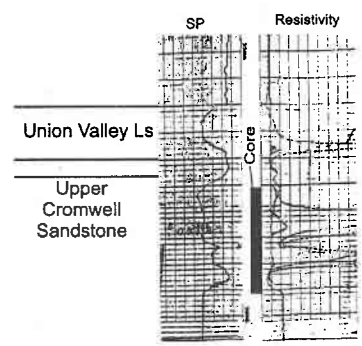


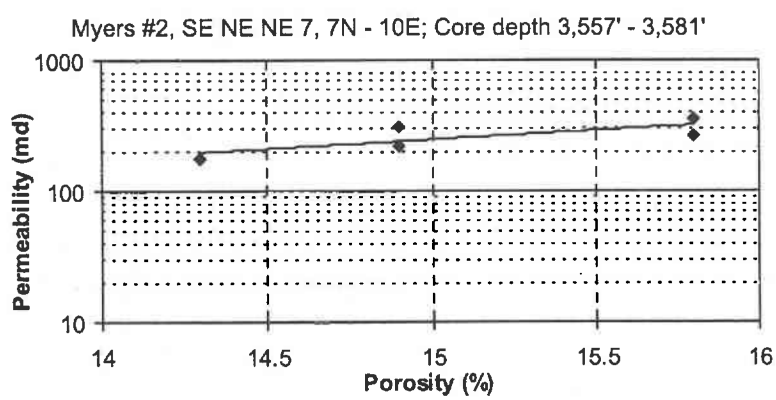












No log or correlative log available

Figure 22. Core porosity and permeability plots of Cromwell Sandstone recovered from four wells drilled by Deep Rock Oil Company. All trend lines are exponential. See Table 2 for actual data.

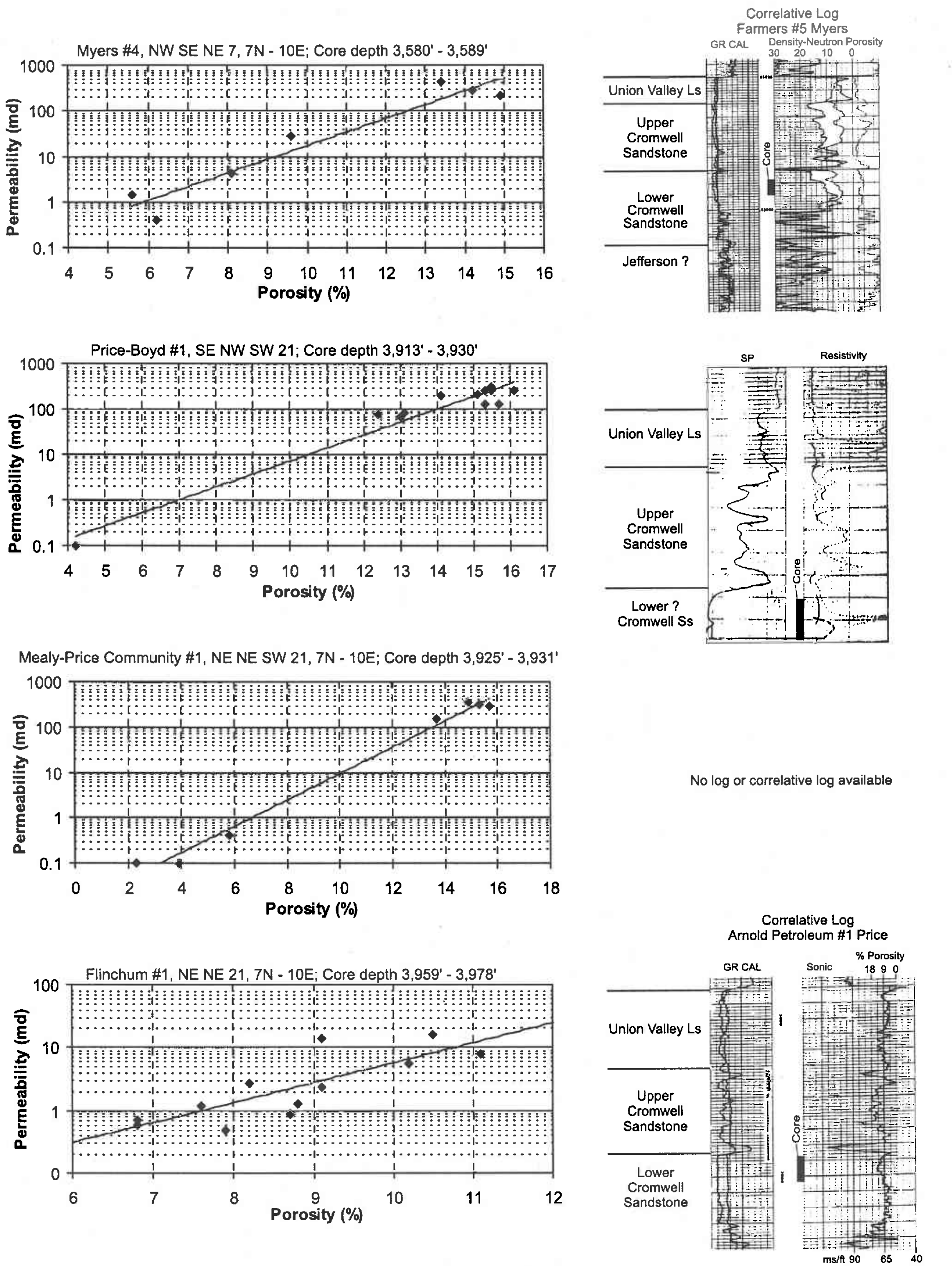


Figure 23. Core porosity and permeability plots of Cromwell Sandstone recovered from four wells drilled by Deep Rock Oil Company. All trend lines are exponential. See Table 2 for actual data.

neutron logs permitted the correlation of core data with down-hole porosity measurements. This is illustrated in Figures 22 and 23. Porosity versus permeability curves were constructed using actual core data; the porosity logs are from nearby "twined" wells. Therefore, actual core depths do not pertain to correlative wells. Original log traces through cored intervals were found for only two of the eight wells and consist of SP and resistivity logs.

DEPOSITIONAL ENVIRONMENTS

This interpretation of depositional environments of the Cromwell Sandstone and equivalent limestone strata is based upon core studies, regional mapping patterns, outcrop examinations, and well log characteristics—particularly gamma-ray logs.

Marine Offshore Bars

Most, if not all, Cromwell Sandstone was deposited in a high-energy, relatively shallow marine environment. Sand was transported eastward into a tectonically restricted shelf embayment probably by incised channels and redistributed by various marine mechanisms including storm currents, long shore, and tidal currents. The sand was deposited in sheets and bars probably miles from shore in as much as sand supply permitted. Therefore, these sandstone deposits appear to be detached from shoreline, which presumably extended through present-day Seminole and northern Pontotoc Counties in a north–south direction. Cromwell bars are generally oriented parallel to the paleo-shoreline in a north–south direction and are often several miles long but only a mile or two wide. Changes in sandstone thickness are most rapid normal to the axis of these types of bars, whereas thickness changes parallel to the bar axis are the least. However, not all Cromwell deposits have this bar morphology. Some appear to be sheet-like without abrupt changes in sandstone thickness. The Cromwell Sandstone does not appear to be deltaic in origin and should not be described in the context of distributary mouth bar or delta front facies.

Amalgamated bar thicknesses in the western part of the Arkoma Basin exceed 250 ft, which by itself would indicate the need for significant accommodation space during deposition. However, sedimentary structures or the lack thereof (described later) are indicative of relatively shallow deposition—perhaps 100 ft or less. The accumulation of sandstone twice this thickness may be explained in terms of multiple but individually rapid depositional events accompanied by comparable basin subsidence. Although local structures generally post-date Cromwell deposition, significant basin adjustments likely occurred during the early Morrowan.

Marine offshore bars are usually diagnostic from well logs, core, and/or outcrop examinations. They are completely encapsulated in marine strata above, below, and laterally. The surrounding rock is usually shale but may also include limestone. Ripple bedding, bioturbation, and trace fossils (Fig. 14 and images from the Austin & Emrick core, Appendix 5) are very abundant in the lower bar facies. No deltaic constituents such as delta-plain deposits (i.e., coal, lagoonal shale, splay sands, etc.) are in stratigraphic continuity immediately above offshore bar sands.

In describing specific zones or facies of offshore bars, terminology is typically lacking or applied in a non-uniform manner. Depositional processes that produce an offshore bar are very similar to those that produce subaqueous shoreface deposits. Therefore, terminology used in this study is "borrowed" from that applied to strandline deposits, knowing full well that offshore bars do not have a shore face because they were deposited away from a shore line.

The typical offshore bar has certain facies that are generally easily recognized. The basal contact is typically gradational with marine shale, which normally underlies the main bar complex. This contact may be very gradual, over tens of feet vertically, or somewhat more abrupt over only a few feet. When gradational, this interval is referred to as the transition zone because of the presence of interbedded sandstone and shale. The amount of shale in the transition decreases upward, giving rise to the characteristic coarsening-upward textural profile. The upper part of a marine bar is variable in thickness and contains relatively clean sandstone that is distinguished by a uniform low gamma-ray log response. Because the final depositional episode of a marine bar often ends quickly or the bar becomes eroded, the upper contact is usually abrupt with marine shale unless multiple bars are deposited upon one another. When the transition zone is absent or poorly developed, the bar is said to have a blocky log profile since both the lower and upper contacts are sharp.

The Cromwell is noteworthy in Oklahoma because the sandstone commonly imparts a blocky log shape on gamma-ray logs. This phenomenon indicates rapid deposition rather than slow, uniform vertical bar accretion. In a marine environment, this texture also is indicative of an abundant sand supply and high depositional energy in the form of currents and wave action. Sedimentary structures such as massive, high-angle cross bed-ding and convolute bedding are typical to these types of deposits. The presence of fossil hash and suspended fossil fragments in the main bar complex also indicates the effects of very strong marine currents and distal transport.

Incised Channels

Cromwell channels have not been identified in outcrop or the subsurface throughout this play. It is believed that they were responsible for the transport of sand into the Arkoma Basin via conduits extending to the northwest but were evidently eroded away with the inception of faulting along the Arbuckle Uplift to the west.

Usually, these types of sandstone deposits are easily recognized by their sharp, eroded basal contacts, blocky log signature (caused by rapid stream abandonment), and narrow but elongate distribution patterns of sandstone. Incised channels also have unique regional relationships; they originate in a landward direction, terminate in a marine environment, and trend basinward. Because they cut deeply into older sediments, they tend to have very rapid lateral facies changes from sandstone to shale in a direction normal to the channel axis. These characteristics are not consistent with Cromwell deposits.

SEDIMENT-SOURCE AREAS (PROVENANCE)

Cromwell Sandstone

Cromwell sediments appear to be sourced from the west–northwest, but no distributary or incised channel systems are identified in this study. The environment of Cromwell deposition is overwhelmingly marine—shallow, high-energy, offshore bars grading into carbonate ramp deposits to the east–northeast.

The interpretation of a northwest provenance is based largely upon sandstone distribution patterns (Pl. 1). At outcrop and in the very shallow subsurface along the western part of the play, the Cromwell Sandstone is >250 ft thick but progressively thins eastward. Through the trough of the Arkoma Basin, the Cromwell gradually becomes increasingly limy and at outcrop near Webbers Falls and Ft. Gibson, the Cromwell equivalent (Morrow) consists mostly of bioclastic limestone in the form of crinoidal grainstone or packstone assemblages. Also in this area, tidal channels and tidal flat deposits are interpreted suggesting a shallowing of the Cromwell sea and possibly subaerial exposure in this part of the play. Little detrital material is believed to have come from the northeast, but there are some Morrow exposures in the Ozark Uplift area of Oklahoma that contain predominantly pure sandstone assemblages in the form of shallow marine bars.

Regional distribution of Morrowan deposits (mostly sandstone and shale) is shown in Figure 24. It suggests that the Morrow was deposited across much of southern Oklahoma but is now absent along a belt extending 10–50 mi on either side of the south-trending Nemaha Ridge and along the Arbuckle Uplift. The southern limit of lower and middle Morrowan sandstone is in the area labeled open marine on Figure 24 and is basinward of the shelf slope to the north. Farther south the equivalent rocks are "washes" or turbidites such as the Jackfork in the Arkoma Basin and the Dornick Hills in the southeast end of the Anadarko Basin.

REGIONAL CROSS SECTIONS

Three regional stratigraphic cross sections show stratigraphy, nomenclature, facies, and character of the Cromwell and Jefferson sandstones (A–A′, B–B′, C–C′, Pls. 4–6). There are two cross sections on each plate and both are "hung" on the top of the Union Valley Limestone. The upper sections show porosity and gamma ray logs of the Cromwell and Jefferson intervals and the bounding units, and some wells also show the PE (photoelectric) log. The lower sections show the same wells but include resistivity and conductivity logs over a much thicker interval encompassing Mississippian through Atokan formations. Diagnostic marker beds bracket the Cromwell and Jefferson intervals to clarify facies changes within the Morrow and facilitate correlation of stratigraphic units. Because each cross section contains a different number of wells, the vertical scale in both the upper and lower sections in each plate is different.

Cross Section A–A′ (Plate 4)

Cross section A–A′ ties outcrops of the Cromwell in the Franks Graben and Lawrence Horst areas to the Morrowan in the Ozark Uplift. The section is oriented southwest to northeast and incorporates 11 wells and four measured sections. This section crosses the Arkoma Basin where it is relatively shallow and illustrates the variations in stratigraphy of the Cromwell–Jefferson interval.

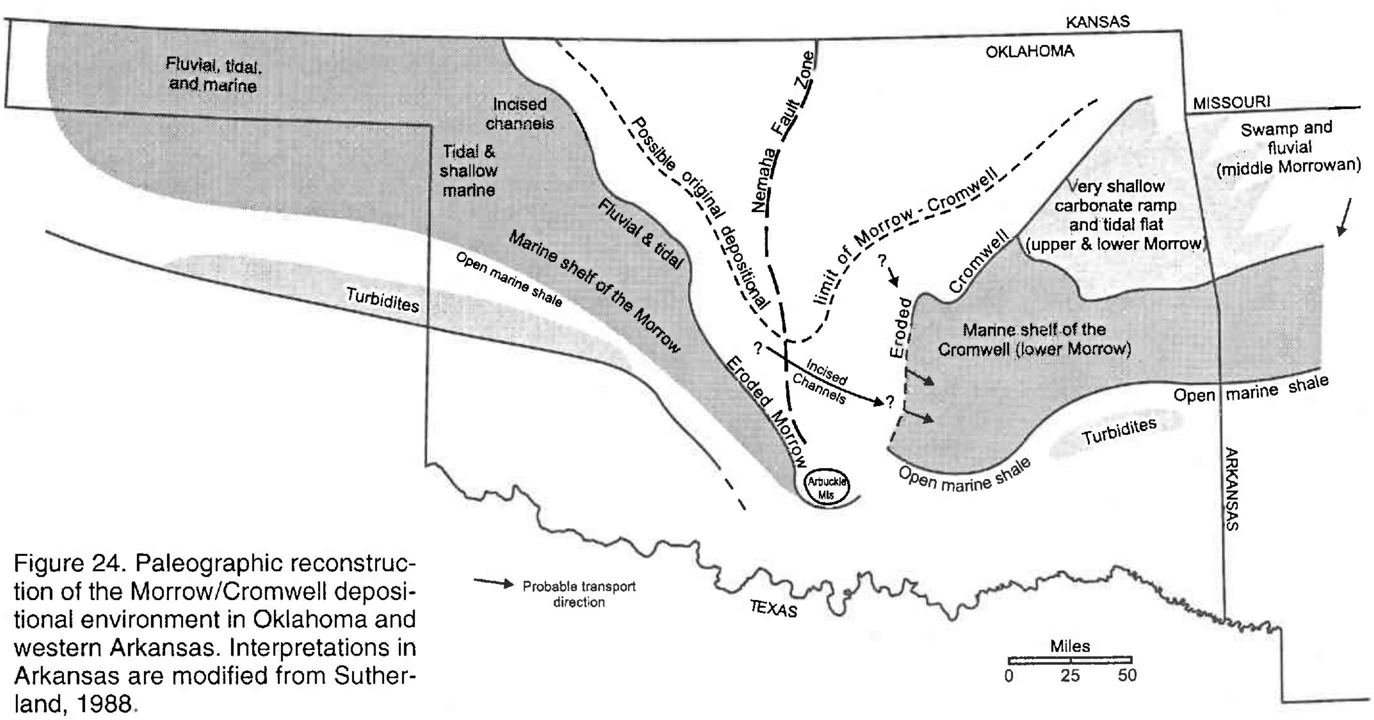


Figure 24. Paleographic reconstruction of the Morrow/Cromwell depositional environment in Oklahoma and western Arkansas. Interpretations in Arkansas are modified from Sutherland, 1988.

A stratigraphic chart appears at each end of this cross section in order to clarify the name changes that occur from one side of the basin to the other.

Starting at the western edge of the Cromwell play in the Franks Graben, the first location is a measured section in the Canyon Creek area. Interpreted by Grayson (1990), the section identifies the complete stratigraphic interval from the Atoka through the Devonian Woodford shale. Thicknesses of the stratigraphic units at this outcrop closely match the interval thicknesses interpreted in nearby well logs, with the exception of the Union Valley Formation. In Canyon Creek, Grayson noted a normal thickness of Union Valley Limestone, but the Cromwell Sandstone was absent. The interval that normally contains the Cromwell consists instead of about 45 ft of shale and silty shale. About 10 mi north at location 2, at another section measured by Hollingsworth (1933), the Cromwell Sandstone was found to be ~240 ft thick. Because of recent road construction and other surface disruptions, this cannot be verified in the field today. Nevertheless, Hollingsworth's measurement is in close agreement with Cromwell Sandstone thicknesses determined in the TDR well at location 3, about 8 mi east of the outcrop. There, the Cromwell Sandstone interval is a little more than 200 ft thick and consists mostly of sandstone with only a few significant shale breaks. In a manner recognized at surface exposures, the sandstone in the TDR well at location 3 has extremely high porosity up to ~24%. The textural pattern indicated on the gamma-ray log shows a distinct coarsening-upward profile in the lower Cromwell and also in the bottom part of the upper Cromwell. Beneath the Cromwell Sandstone, the Springer shale is easily recognized by its low resistivity. Beneath the Springer shale at location 3 there is a relatively thick Jefferson sandstone interval >80 ft thick, comprised of numerous thin sandstone beds and interbedded shale. Almost 10 mi farther east, the Cromwell interval thins significantly in the Geodyne well at location 4. This may be due to local structure that was active after Cromwell deposition (the Jefferson does not seem to be affected at this location). At location 5, the TXO well has a Cromwell and Jefferson section similar to that at location 3. The only significant break within the Cromwell Member is a thin shale bed at the boundary between the upper and lower sub-members. In the TXO well at location 5, both the upper and lower Cromwell and the lower Jefferson sandstone zones have very sharp basal contacts with shale—something more typical of an incised channel than a marine bar. The equivalent sandstone zones in nearby wells lack this sharp basal contact and instead have a coarsening-upward textural profile in the lower Cromwell. Note that at locations 4 and 5 an additional sandstone interval develops in the upper Goddard Shale interval.

At location 6 the Cromwell and Jefferson intervals are considerably thinner and the amount of sandstone also has diminished. Practically every sandstone zone in that well is perforated and productive, suggesting a nearby trap. As in the previous three wells, the Union Valley Limestone rests directly on top of the Cromwell Sandstone, and the contact is best defined using porosity logs since the limestone has very little porosity compared to the sandstone. About 14 mi to the northeast at location 7, the upper Cromwell Sandstone becomes a single thick bed and the lower Cromwell Sandstone is completely replaced by shale. Almost 21 mi to the northeast at location 8, both sub-members are again present and have a blocky and/or slightly coarsening-upward textural profile typical of most Cromwell sections. In the Andress well at location 8, the Cromwell Sandstone has <8% porosity (ϕ) and is probably limy, yet it is still productive. The upper Cromwell Sandstone is absent in all the logs in this cross section northeast of the Andress well, whereas the lower Cromwell and Jefferson sandstones are present several miles farther to the northeast.

Stratigraphic changes are dramatic as the line of cross section approaches the Ozark Uplift. In the Unit Drilling well at location 10, the Union Valley Limestone and entire Cromwell interval thin considerably, as does the Jefferson. In the distance of only 3.4 mi, the Cromwell Sandstone completely disappears and is replaced by shale and thin limestone beds. The "False" Caney changes facies to mostly limestone, but the Jefferson sandstone and Goddard shale continue to be recognizable. Between locations 11 and 12 (a distance of only about 7 mi), the Jefferson sandstone and underlying Goddard shale are apparently discontinuous and possibly truncated beneath the Springer shale. As correlated in the Service Drilling well at location 12, the Springer shale is interpreted by the strong neutron log response on the upper cross section and by a strong conductivity log response on the lower cross section. This same shale section appears correlative to the basal shale in the lower part of the Braggs member in the measured section at Webbers Falls of location 13. Limestone underlying this shale interval is believed to correlate to the Pitkin Limestone.

Location 13 is a surface section at Webbers Falls measured by Sutherland (1979), and many of the stratigraphic units there appear to correlate to subsurface well logs at location 12, ~11 mi south, and at location 14, ~4.6 mi to the north. Location 14 is a strategic location for subsurface control because the well log can be correlated to outcrops at both locations 13 and 15. The principal correlative units are the shales and the Pitkin Limestone.

The lower part of the Braggs Member in the Braggs Mountain section (location 15) has sandstone resting directing on top of the Pitkin limestone. This sandstone appears to shale-out to the south and is believed to be approximately equivalent to the Jefferson sandstone horizon in the Ensign well at location 11. If this is so, the Jefferson and overlying Cromwell intervals are equivalent to limestone and shale intervals in the middle and lower parts of the Braggs Member of the Sausbee Formation. The actual measured sections of Sutherland (locations 13 and 15) are shown in Figure 25.

In summary, cross section A–A′ shows these important stratigraphic concepts:

1) The Union Valley Limestone appears to be correlative to an upper limestone in the Braggs Member of the Sausbee Formation.

2) The Cromwell Sandstone can occur as a massive sandstone unit with few internal shale breaks. Locally,

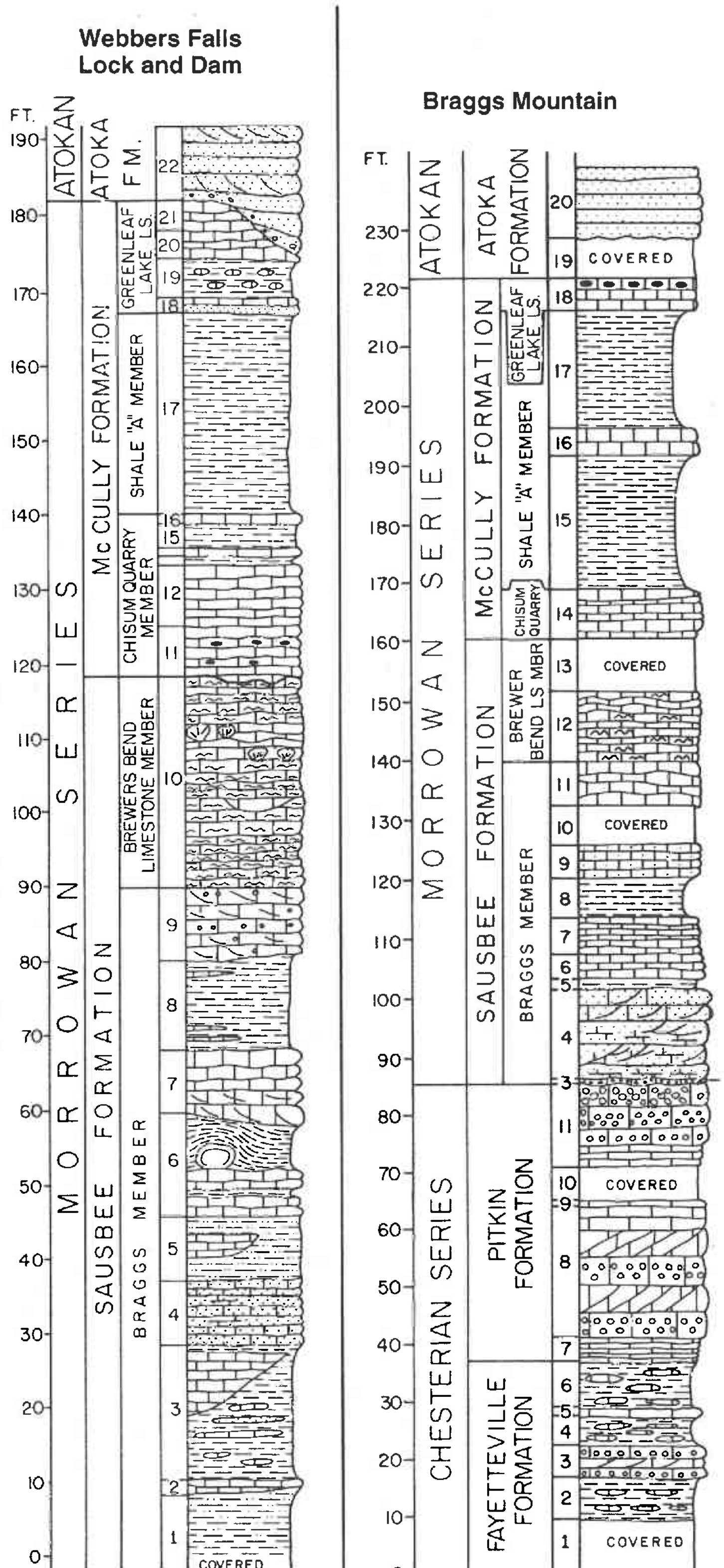


Figure 25. Detailed measured sections of the Morrowan Series at the Webbers Falls lock and dam site and at Braggs Mountain. Webbers Falls lock and dam section measured by P. K. Sutherland and T. W. Henry. Braggs Mountain section stratigraphic units 1–11 measured by A. H. Orgren; stratigraphic units 3–20 measured by D. A. Kotila. From Sutherland (1979).

the distinction between upper and lower Cromwell is arbitrary.

3) The upper Cromwell Sandstone is absent northeast of R. 17 E.

4) In some places the textural profile of the basal Cromwell Sandstone is sharp and appears erosional; elsewhere it is gradational.

5) The low resistivity Springer shale separates the Cromwell from the Jefferson, and a similar Goddard shale separates the Jefferson from the "False" Caney. These shales also occur in the Anadarko Basin.

6) The Union Valley Limestone is present throughout this cross section. It may contain interbeds of shale locally.

7) The Jefferson interval contains numerous sandstone beds, particularly in the western and deeper parts of the Arkoma Basin. They are oil and gas reservoirs locally.

8) The Cromwell Sandstone and Jefferson sandstone intervals are equivalent to crinoidal limestone and shale intervals of the Sausbee Formation in the Ozark uplift area.

9) The Pitkin Limestone correlates with the calcareous facies of the "False" Caney.

10) The Caney shale correlates with the Fayetteville Shale, and the Hindsville Limestone is equivalent to the Mayes and Sycamore limestones.

Cross Section B–B′ (Plate 5)

Cross section B–B′ (Pl. 5) is a north-to-south, dip-oriented section. It ties with section A–A′ and crosses C–C′ (Pls. 4–6) in the shallow western part of the play area. Thirteen wells were selected to show the character of the Cromwell interval, regional unconformities, and facies changes that occur from the Cherokee Platform in the north to the southern edge of the Arkoma Basin in the south. Because so many changes occur spatially within the Morrowan, it was necessary to identify marker formations in the bounding Atoka and Mississippian strata in order to accurately correlate and understand facies relationships in the Cromwell and Jefferson intervals.

The first four wells in cross section B–B′ are north of the subcrop limit of the Cromwell Sandstone. The obvious unconformable relationship between the Union Valley Limestone and the truncated Cromwell Sandstone is evidence of a period of erosion that erased the fluvial incised channels discussed in the sections "Depositional Environments" and "Sediment-Source Areas (Provenance)." Above the Union Valley Limestone there is persistent thin shale identified as the Wapanucka shale that increases in thickness from 20 ft in the northern wells to >400 ft in the southern wells.

The first well having recognizable Cromwell Sandstone is the Templex well at location 5. At this location there appears to be <10 ft of upper Cromwell Sandstone overlain by ~70 ft of Union Valley Limestone. The unconformable contact between those two units is picked at a porosity break at 2,842 ft, but it may be even higher in the section. Below the upper Cromwell Sandstone there is about 38 ft of lower Cromwell Sandstone that has porosity of 12–15% as noted on the density-neutron logs. The

Springer and Jefferson intervals are missing below the lower Cromwell in this area either by onlap or by erosion. Limy shale that underlies the lower Cromwell Sandstone appears to be Goddard equivalent, but an alternative interpretation is that it is part of the "False Caney." At location 6, 10 mi farther to the south, the Union Valley Limestone is ~90 ft thick and is characterized by low porosity in the upper half grading downward into strata having increasing porosity. The top of the underlying upper Cromwell Sandstone is picked where porosity suddenly increases from ~6% to almost 10%. A thin zone in the center of the upper Cromwell Sandstone has 16% ϕ, but low resistivity indicates that it is wet. About 20 ft of shale separate the upper from the lower Cromwell, which is ~50 ft thick. Several zones have porosity of 15–17%, all wet. The northernmost Jefferson sandstone occurs in this well, although it is only 5 ft thick and tight. The underlying Goddard Shale appears normal on both the resistivity and porosity logs and is not limy as it is in the well to the north. In the C & M well at location 7, both the upper and lower Cromwell Sandstone have better porosity than in the wells to the north. At location 7 the upper Cromwell has a distinct coarsening-upward textural profile, while the lower Cromwell has a sharp basal contact and a fining-upward profile. The contact with the overlying Union Valley Limestone is not well defined and is picked where the accompanying PE log shows values changing from <2 to >3. Note that the Jefferson sandstone, although thin, is perforated in the C & M well and produced maybe half of the estimated 0.3 BCF gas that is commingled with the Gilcrease.

In a basinward direction, the TXO well at location 8 is near the southern edge of the Cherokee Platform. Only 6 mi south of this well, at location 9, the Cromwell, Jefferson, Goddard, and "False" Caney have all thickened considerably going into the Arkoma Basin where "hot" shale marker beds on gamma-ray logs are used to distinguish correlative stratigraphic intervals. Another 8 mi into the basin at location 10, the Cromwell interval in the Murexco well is nearly 200 ft thick and consists mostly of sandstone. Because of several prominent shale breaks in the middle part of the Cromwell interval, it is difficult to distinguish between upper and lower Cromwell at location 10. Some of these shale breaks are absent in the TXO well at location 11, and even fewer occur in the Wagner & Brown well at location 12. Recognition of porous and/or tight zones in these massive sandstone intervals may be useful in correlating zones from one well to another. The thick Cromwell Sandstone accumulations in wells 10, 11, and 12 make interpretations of depositional environments difficult other than indicating that the wells penetrated a thick marine bar complex. Without other evidence to the contrary, Cromwell Sandstone in wells at locations 10–12 could even be interpreted as incised channel fill deposits (although they are not) because of their sharp basal contacts and blocky log signatures.

The Jefferson in the TXO well at location 11 is extremely well developed and has two main intervals, each comprised of multiple sandstone zones. The lower Jefferson interval has three sandstone zones, each having sharp basal contacts and upward fining textural profiles as determined on the gamma-ray logs. This contrasts with equivalent sandstone zones in wells at locations 10 and 12, where coarsening-upward textural profiles are apparent. Variations in the log profiles are probably the result of different depositional conditions and because of facies changes in the bars. In the TXO well at this location, sandstone also extends into the upper half of the Goddard Shale interval.

The Cromwell and Jefferson intervals in the Wagner & Brown well at location 12 are almost 7,000 ft deep. The upper Cromwell interval in this well thins considerably and the lower Cromwell consists of massive sandstone with few significant shale breaks. As usual, highly conductive shale separates the Cromwell from the underlying Jefferson. This shale is particularly evident in the Wagner & Brown well and in wells at locations 11 and 13. The well at location 13 is located only 6 mi northwest of the Choctaw Fault, and the thickness of the Cromwell Sandstone is diminished considerably. At outcrop just south of the Choctaw Fault, the Cromwell equivalent consists almost entirely of shale with only a few thin, tight sandstone beds. The very southern part of the present Arkoma Basin was apparently far from a clastic source area and was near the Morrowan depo-center.

In summary, cross section B–B′ shows these important stratigraphic concepts:

1) The Cromwell Sandstone Member consists of two distinct sandstone intervals, usually separated by a shale break. Locally, however, the shale is missing and the break is difficult or impossible to determine.

2) Low resistivity shale separates the Cromwell from the Jefferson, and the Jefferson from the Goddard Shale. This relationship is similar to that between the Morrow and the Springer in the Anadarko Basin.

3) A regional unconformity exists at the top of the upper Cromwell Sandstone. North of the subcrop of the Cromwell Sandstone the unconformity extends into the underlying Caney shale, and the inferred incised channels are lost.

4) The Cromwell Sandstones have a variety of upper and lower contact relationships; in some places they are sharp, in other places they are gradational.

5) Along the northern flank of the Cromwell play, the Union Valley Limestone locally exceeds 100 ft in thickness. In this area, the Union Valley Limestone is frequently productive from thin porous intervals.

6) In the deep basin, the Jefferson sandstone interval thickens to >100 ft and locally becomes a good reservoir.

7) The Cromwell interval thins and the amount of sandstone diminishes considerably to the south near the Choctaw Fault.

8) Because the combined thickness of the Cromwell and Jefferson intervals vary only a few hundred feet from shelf to basin, the Arkoma Basin during lower Morrow time was not rapidly subsiding.

Cross Section C–C′ (Plate 6)

Cross section C–C′ (Pl. 6) is an east-to-west strike-oriented section that intersects both A–A′ and B–B′ near the center of the play. It consists of 12 subsurface well logs and begins west of the subcrop limit of the Cromwell and ends near the Arkansas border to the east where the Cromwell consists largely of shale. This cross section also includes stratigraphic nomenclature charts at both ends. Note that in most wells where the Cromwell Sandstone is well developed, it has fairly sharp lower and upper contacts.

The westernmost well in cross section C–C´, at location 1, shows a regional unconformity between the onlapping Desmoinesian Savanna Formation and underlying Mississippian "False" Caney shale. At this location, the entire Union Valley Formation is absent. The Cromwell first appears at location 2 in the Archibald well, 8.5 mi to the east. Here, the Cromwell is about 130 ft thick and is further subdivided into an upper and lower sub-member. This distinction is based solely on a prominent shale break separating the porous upper Cromwell (ϕ 16–18%) from the much tighter lower Cromwell. The Union Valley Limestone overlies the Cromwell and is about 25 ft thick. It is easily differentiated from the Cromwell by the porosity log but most convincingly by the PE log, which shows values between 4 and 5 for limestone and values between 2 and 3 for the Cromwell Sandstone. The Union Valley Limestone at location 2 appears to be overlain by a very thin section of Wapanucka shale.

At locations 3 and 4, the Cromwell thickens to about 100 ft, mostly in the upper Sandstone sub-member which has excellent porosity. Note the thickening of the Wapanucka shale from 20 ft in well 2 to 230 ft in well 4. Between locations 4 and 5, both the Union Valley Limestone and Cromwell Sandstone thicken over a distance of ~18 mi. In the Stover well, location 5, the Union Valley Limestone is 80 ft thick, and the Cromwell is >140 ft thick. The upper part of the upper Cromwell is tight and probably limy, whereas the lower part of the upper Cromwell has excellent porosity of >20%. The tight part of the upper Cromwell can be distinguished from the Union Valley Limestone on the basis of the PE log curve where the Union Valley Limestone has values of ~5, and the tight Cromwell Sandstone has values of 2 to 3. The Lower Cromwell is also limy and tight, but the PE log clearly indicates a sandstone matrix. The Jefferson sandstone first appears beneath the Cromwell Sandstone at location 5 and is separated from the Cromwell by regionally persistently low resistivity shale, the Springer shale. In the Stover well at location 5, the Jefferson has two distinct sandstone zones that locally become good gas reservoirs. The underlying Goddard Shale is picked at the first occurrence of uniformly bedded, low resistivity shale beneath the Jefferson sandstone. Significant changes develop in the Union Valley Limestone and the Cromwell Sandstone in the 18 mi between locations 5 and 6. In the Scout Energy well at location 6, the Union Valley Limestone contains a shale split near the top, and porosity develops in the thick lower part. That porosity makes it difficult to pick the contact with the porous upper Cromwell, because it is similar to porosity occurring in sandstone. The porous zone extends down ~32 ft, but the rock again becomes tight thoughout an 18-ft limestone interval interpreted to be the lower part of the Union Valley Member. Beneath this limestone, a porosity break occurs in sandstone at 4,364 ft, which is considered to be the top of the Cromwell. Within this member, there is good porosity in the lower part of the upper Cromwell and in the upper part of the lower Cromwell. Slightly more than 20 ft of shale separates the Cromwell from an underlying sandstone interval herein identified as the Jefferson. The Jefferson interval contains ~40 ft of sandstone in an upper bed and almost 20 ft of sandstone in a lower bed. This thickness of sandstone is unusual for the Jefferson, and some geologists may alternatively identify the upper Jefferson in wells 5 and 6 as lower Cromwell. Nonetheless, the high conductivity of the shale unit separating the Jefferson from the Cromwell is distinct in this area and is consistent with the Springer shale that separates the two sandstone intervals.

The Union Valley Limestone at location 7 is difficult to recognize because it is divided into two thin benches of limestone separated by almost 50 ft of shale. The underlying Cromwell Sandstone has numerous thin shale partings but no major shale breaks that can be used to distinguish between the upper and lower sub-members. The distinction in this case may be the recognition of a porous zone near the bottom half of the upper Cromwell sandstone that is correlative between wells at locations 4, 5, and 6. The Jefferson interval and included sandstone at location 7 thins significantly compared to wells at locations 5 and 6, which are farther basinward. At location 8, the sandstone in the upper Cromwell interval is absent and is replaced by shale. The lower Cromwell Sandstone thickens slightly and has an overall fining upward textural profile. This textural pattern also is seen in the lower Cromwell intervals in wells 5 and 6. Almost 12 mi east of location 8, in the Roye well at location 9, there is ~80 ft of upper Cromwell Sandstone that has the characteristic coarsening-upward textural profile common to marine bars. The lower Cromwell Sandstone at location 9 also has this distinct textural profile throughout most of its 40-ft thickness. The Jefferson interval is thin but is still recognizable between the low resistivity shales of the Springer and Goddard. These relationships continue beyond the Terra well at location 10. At location 10 the underlying Mississippian Caney shale has thinned considerably, and the lower part of the "False" Caney has become mostly limestone instead of shale. These changes in the Mississippian units first appeared several miles to the west in the Roye well at location 9.

The stratigraphy continues to change in the 10.6 mi between locations 10 and 11. In the Stephens well at location 11, the upper Cromwell Sandstone is nearly shaled-out and the interval is replaced by open marine shale and distal bar facies as suggested by the very gradual coarsening-upward textural profile and minimal sandstone at the very top of the sequence. Similarly, the lower Cromwell interval consists of only two thin sandstone zones overlying ~50 ft of marine shale and distal bar facies. The thin Jefferson interval can only be recognized on the resistivity log. The Goddard shale appears to have pinched out someplace between locations 10 and 11, and the Caney shale has thinned to only about 50 ft at location 11; it was nearly 200 ft thick in the Questar well at location 8. The

"False" Caney interval at location 11 is mostly limestone and the basal contact with the Caney shale is not clear. The easternmost well in cross section C–C´, the TXO well at location 12, shows only ~10 ft of sandstone and ~100 ft shale in the upper Cromwell interval. The lower Cromwell interval has ~80 ft of irregularly bedded sandstone resting on Springer shale. The "False" Caney is almost entirely limestone at this location and is equivalent to the Pitkin Limestone that crops out ~30 mi to the north.

In summary, cross section C–C´ shows these important stratigraphic concepts:

1) The Union Valley Limestone appears to be correlative to an upper limestone in the Braggs Member of the Sausbee Formation.

2) The Cromwell Sandstone Member consists of two distinct sandstone intervals, often separated by a prominent shale bed. Locally, however, the shale is missing and the break is difficult or impossible to determine.

3) The log profiles of the Cromwell sandstones show a variety of upper and lower contact relationships; in some places the contacts are sharp, other places they are gradational.

4) Low resistivity, high conductivity shale separates the Cromwell from the Jefferson, and the Jefferson from the "False" Caney. This relationship is similar to that between the Morrow and Springer in the Anadarko Basin.

5) The "False" Caney is a shale interval characterized by alternating high and low resistivity beds throughout most of the Arkoma Basin. To the east, it changes facies and becomes mostly limestone that is equivalent to the Pitkin Limestone.

6) The Caney shale is the equivalent of the Fayetteville Shale.

7) The Mayes or Sycamore Limestone in the west correlates with the Hindsville Limestone in the east.

8) Approaching the Wilzetta Fault zone to the west, a major unconformable surface is defined by the erosion of the entire Union Valley Formation and upper Chesterian. In this same area, the overlying Desmoinesian appears to onlap the unconformity so that the Savanna overlies the "False" Caney.

STRUCTURE

The Cromwell play occurs across the Arkoma Basin of southeastern Oklahoma and extends into provinces northeast of the Arbuckle Uplift. Local structures control most hydrocarbon accumulations in the Cromwell play. The Wapanucka Structure Map (Pl. 3) depicts the regional structure of the Wapanucka Limestone, which mimics the structure of the underlying Union Valley Formation. The Wapanucka Limestone is regionally extensive throughout most of the study area and is a convenient horizon 200–300 ft above the top of the Cromwell on which to map structure.

The map was constructed by modifying structural interpretations of Rottmann (2001) and Shenk (2001) with log tops retrieved from the Natural Resources and Information System (NRIS), a database developed at the University of Oklahoma. These data were supplemented in the local field studies with picks from numerous well logs. The structure map was hand contoured and verified with well data in field study areas (star symbols on Pl. 3) and in wells comprising the three regional cross sections. The locations of wells (solid squares) with Cromwell core descriptions (Appendix 5) and the lines of regional cross sections A–A´, B–B´, and C–C´ (Pls. 4–6) also are shown on both the regional structure and Cromwell Sandstone maps.

The overall regional dip is to the southeast with a maximum subsea depth below 16,000 ft just north of the trace of the Choctaw Fault. The deepest "holes" exist in the Kiowa Syncline (T. 4 N., R. 15 E.) and south of the Hartford Anticline in T. 5 N., Rs. 25–26 E. Minor folds and faults developed in the shallow basin and shelf areas during Cromwell time while structural movement was much more intense in the eastern and western parts of the play. South of the Choctaw Fault the Cromwell and Wapanucka are repeated by thrust faults. The Cromwell and Wapanucka intervals are more faulted and deformed than the stratigraphically higher Hartshorne and Booch formations. Evidently, the thick Atoka shale "absorbed" much of the structural "punishment" recognized in the deeper rocks.

Fault displacement in the Cromwell play range from <100 to >2,000 ft. There are numerous small faults not included on this map because of their immense complexity and abundance. Faults are generally oriented parallel or semi-parallel to the axis of the Arkoma Basin in a northeast–southwest direction, particularly in the eastern half of the study area. Relative movement on most of these faults is down to the south, basinward, but there are many exceptions as indicated in Plate 3. At the Cromwell level in the Arkoma Basin, most fault throws appear to be essentially vertical since repeated sections were not identified on well logs by the author. In some wells within the basin, normal faulting was suspected because of the absence of certain strata. In the western part of the area along the flanks of the Arbuckle Uplift, the major faults are oriented northwest to southeast or sub-parallel to the outcrop belt south of Ada. Additionally, some faults appear to have relative *lateral* movement west of the Franks Graben area as evidenced by shifts in the outcrop patterns. However, this movement may simply be apparent due to vertical displacement along dipping fault planes. The Holdenville and Keokuk Faults on the Cherokee Platform in the west part of the Cromwell play are oriented north to south. Some faults can be mapped at the surface (Fig. 26) and the major ones commonly have zones of fracturing and small-scale faults such as shown in Figure 27.

Faulting occurred intermittently within the Arkoma Basin during the Pennsylvanian Period. Evidence for this can be interpreted from regional cross sections of this report that transect adjoining provinces and fault zones. Although these sections are stratigraphic rather than structural, significant changes in formation thickness and extent provide evidence of structural movements. Regional cross section A–A´ (Pl. 4) shows continuous deposition during Morrowan time across most of the Arkoma Basin and Ozark uplift. On this plate, the only significant variations are facies and formation thickness and both

Figure 26. Normal fault exposed along the west cliff at Webbers Falls lock and dam.

Figure 27. Small-scale fault exposed in a road cut south of Ada, Oklahoma.

factors relate to depositional environment. However, regional cross sections B–B´ and C–C´ (Pls. 5, 6) illustrate the development of unconformities above the Union Valley Limestone and upper Cromwell Sandstone. In cross section B–B´ (Pl. 5) the upper Cromwell Sandstone is shown to be eroded northward as the Cherokee Platform is approached. This indicates that uplift and erosion occurred during early to middle Morrowan time and that a regional unconformable surface overlies the Cromwell Sandstone. In cross section C–C´ (Pl. 6) the entire Union Valley Formation including the Union Valley Limestone is shown to be eroded along structural elements east of the Arbuckle Uplift and Wilzetta Fault Zone. This indicates that the Union Valley Limestone also is overlain by a regional unconformity. Evidence of local faulting during or just after deposition of the Union Valley Formation is also documented in the Scipio Field study accompanying this report. Moreover, all or part of the Atoka, McAlester, and Savanna Formations onlap the Union Valley unconformity successively to the west in cross section C–C´ (Pl. 6). Displacement, interval thinning, and discontinuance of these formations is greatest in the older Atoka Formation, diminished in the younger Savanna Formation, and not apparent (in this section) in the overlying Boggy Formation. These relationships demonstrate that major structural events in provinces east of the Arbuckle Uplift are largely pre-Boggy in age.

SUMMARY OF REGIONAL CROMWELL MAPS

Plate 1 shows the regional distribution and the approximate thickness of gross sandstone within the Cromwell Sandstone Member exclusive of interbedded shale. Some Jefferson sandstone may have been incorporated in this thickness determination because of miscorrelation during the preliminary assessment of this play. Plate 1 also includes notations about significant lithofacies and shows the principle bounding faults, outcrop patterns, locations of the field studies, locations of cores described in Appendix 5, and lines of the regional cross sections (Pls. 4–6). Plate 2 is a production code map showing the allocation of oil and gas production from the Cromwell, Jefferson, and Union Valley reservoirs based on NRIS data. On this map, Cromwell production is colored red (gas) and green (oil); Jefferson production is colored orange (gas); and Union Valley production whether gas or oil is colored blue. Plate 3 is a regional structure map depicting the structure at the top of the Wapanucka Limestone—a regionally extensive marker bed 200–300 ft above the Cromwell Member. Data used to construct this map were derived primarily from NRIS and supplemented locally by published and proprietary structure maps, and field study maps of this publication.

Plates 4, 5, and 6 are regional cross sections (A–A´, B–B´, and C–C´) that illustrate the log character, facies relationships, and stratigraphy of the Union Valley Formation and bounding formations.

Plate 7 is a map showing the location and names of oil and gas fields producing from the Cromwell and/or Jefferson. Field names and boundaries are from Boyd (2002) as determined by the Oklahoma Stratigraphic Nomenclature Committee of the Mid-Continent Oil and Gas Association. In some cases, field boundaries are not relevant to the areal distribution of Cromwell or Jefferson reservoirs. In other cases, Cromwell production is found outside formal field boundaries, because the definition of field boundaries often lags behind the extension of producing areas.

All available sources of information were used in completing this study, including information from the private domain, theses, consultants, and personal investigations by the author. Approximately 2,000 well logs were used to construct the isopach and structure maps, field studies, and regional cross sections of Plates 1, 3, and 4–6. Outlines of published and proprietary studies that contain subsurface or surface mapping relevant to the Cromwell play are shown in Plate 8.

Throughout this paper, references are made to various sand-size grades in the description of certain rock units; they are listed in Appendix 2. Similarly, various abbreviations and terms that are used in this paper are defined in Appendices 3 and 4. Two cores are provided for examination by workshop attendees, and brief descriptions and facies interpretations are given, along with well logs and selected visual images, in Appendix 5.

SIMILARITIES BETWEEN THE CROMWELL IN THE ARKOMA BASIN AND THE MORROW IN THE ANADARKO BASIN

(Refer to Figure 3 regarding some of these attributes.)

1) The Morrow Group in both basins has a shaly upper half and sandy lower half.

2) A limestone zone occurs in the middle of the Morrow Group immediately above the lower sandstone interval; in the Arkoma Basin it is called the Union Valley Limestone, and in the Anadarko Basin it is called the Squaw Belly.

3) High conductivity, low resistivity shale (Springer shale) occurs beneath the Morrow Group in both basins.

4) Detached, shallow marine bars constitute the dominant sandstone facies.

5) High conductivity, low resistivity shale also underlies the upper Springer sandstone in each basin, i.e., beneath the Jefferson and Cunningham sandstones.

6) In places, only 40 mi separate the Anadarko Basin from structural provinces adjacent to the Arkoma Basin. It seems likely that the depositional system that dominated during the Morrow was contiguous throughout most of southern Oklahoma.

PART II

Scipio NW Field

Upper Cromwell and Jefferson sandstone gas reservoirs in T. 8 N., R. 13 E., southwest McIntosh County, Oklahoma

INTRODUCTION

Scipio NW Field is about equal distance between McAlester and Henryetta in the southwest corner of McIntosh County, southeastern Oklahoma (Fig. 28). The 64-section study area is in the N½ of T. 8 N., R. 13 E., and located near the center of the Cromwell play and Arkoma Basin as shown in Plate 1. The study area includes four closely spaced but separate gas pools along upthrown fault blocks. Areas producing from the Cromwell and Jefferson reservoirs constitute only part of the officially recognized Scipio NW Field as established by the Okla-

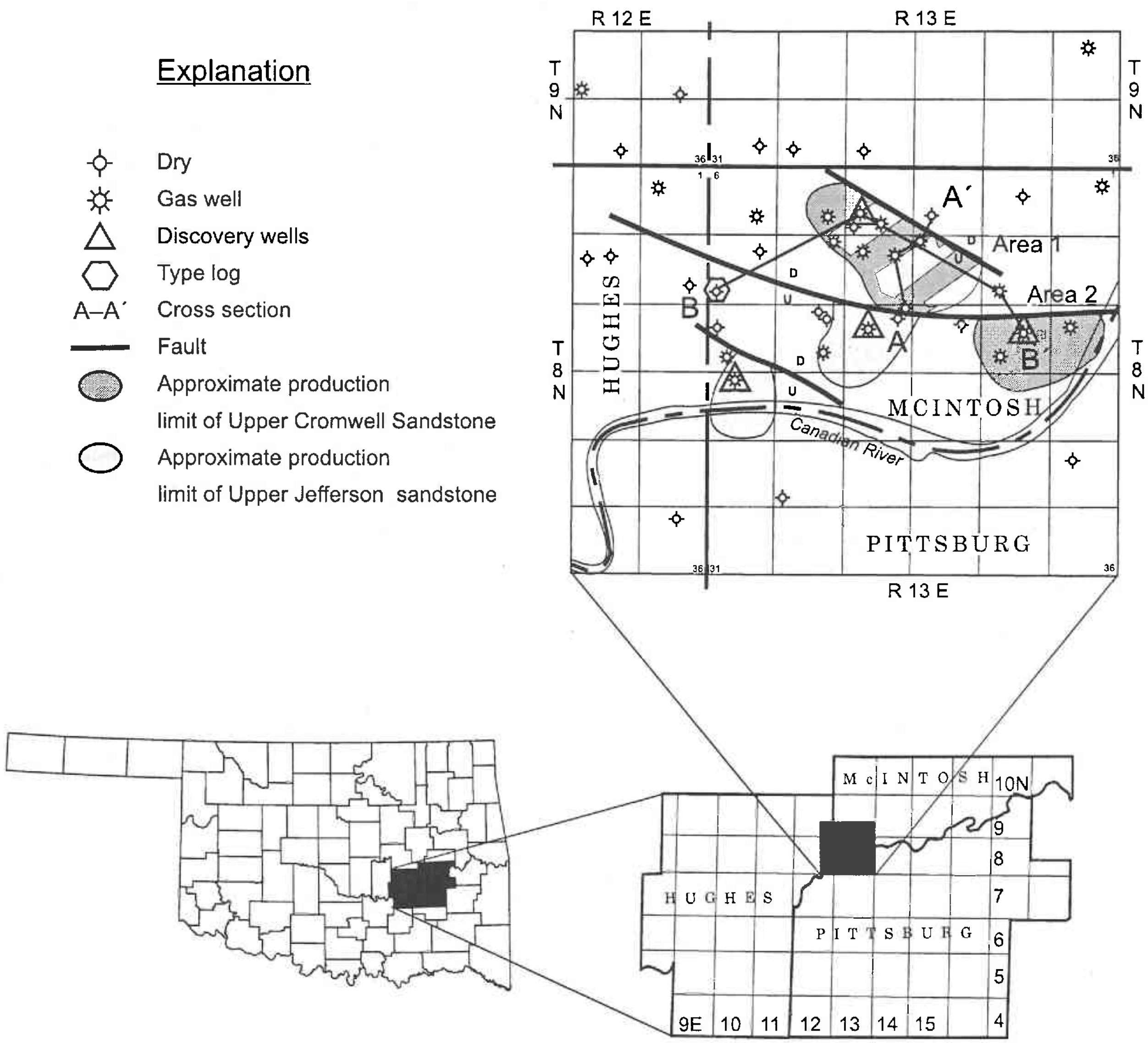


Figure 28. Generalized location map of Scipio NW Field, southwest McIntosh County, Oklahoma. Lines of cross sections A–A′ (Fig. 32) and B–B′ (Fig. 33) are shown.

homa Stratigraphic Nomenclature Committee of the Mid-Continent Oil and Gas Association. This happens because other reservoirs produce elsewhere in the field including the younger Savanna, Booch, Union Valley Limestone, Wapanucka Limestone, Gilcrease sandstone, and Spiro sandstone. The locations of wells producing from the Cromwell and Jefferson are shown on Figure 29, but only those penetrating the Cromwell and Jefferson are included on maps in this study. The productive limits of the individual gas pools are defined on the basis of geologic interpretations from well logs; seismic was not used to define the faults. Dry holes, non-producing, and under-producing Cromwell zones are usually the result of reservoirs being structurally low and wet. Less frequently, the

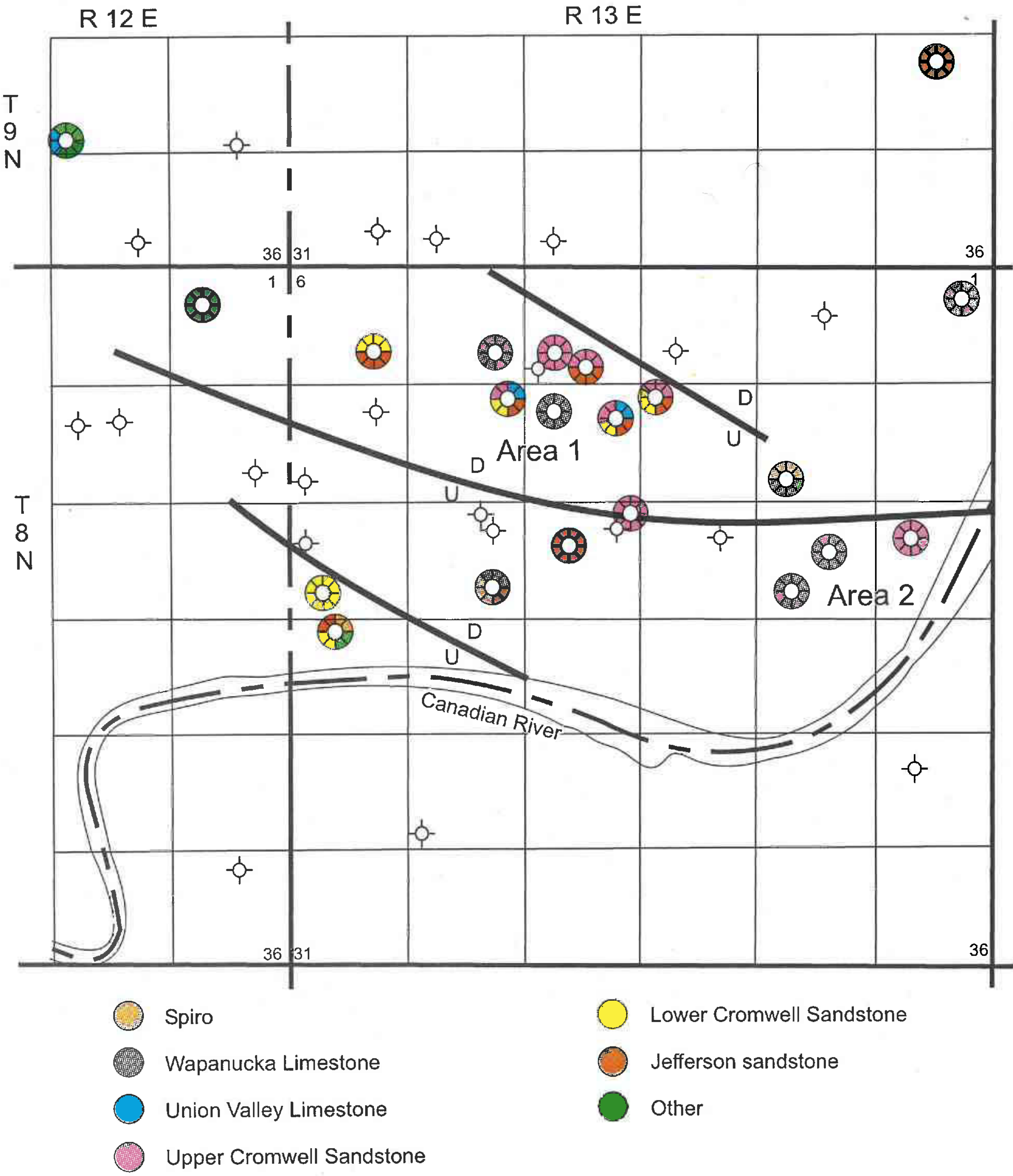


Figure 29. Production code map showing producing reservoirs in Scipio NW Field, southwest McIntosh County, Oklahoma.

sandstone is tight or pressure depleted—a condition that can usually be identified from porosity and resistivity logs.

As a general rule, the Cromwell reservoir in Scipio NW Field produces in areas along upthrown fault blocks where the gross Cromwell Sandstone is *thinnest*. Therefore, mapping sandstone strictly for the purpose of predicting stratigraphically trapped hydrocarbons is not applicable in Scipio Field or in many other places in the Arkoma Basin. It should be noted that some parts of the basin are entirely devoid of Cromwell production despite the widespread occurrence of porous sandstone. Nevertheless, it is always important to know the distribution pattern of reservoirs to assist development and exploration drilling.

Cumulative gas production from the upper Cromwell Sandstone in Areas 1 and 2 (Fig. 28) is about 9.2 BCF. The underlying Jefferson sandstone has produced perhaps 750 MMCFG and is not a primary objective in this area.

The best reservoir in Scipio NW Field is the upper Cromwell Sandstone. The highest-volume wells have the thickest *net* sandstone, are structurally high, and were completed early in the development history of the field when reservoir pressure was greatest. There are no good late-stage development wells in the field. Cumulative production from individual wells drops off from a high of >3 BCF for wells drilled in 1971 to about 0.25 BCFG for wells drilled in 1995. One well drilled in 1999 produced only 21 MMCFG. The formation pressure in the Cromwell Sandstone throughout this field is essentially depleted.

As of February 2002, there were 11 wells producing from the upper Cromwell; eight in Area 1, and three in Area 2. Only two wells were completed in the lower Cromwell in the entire area, and eight wells found production in the underlying Jefferson. Multiple-zone completions happen in more than half of the wells, which makes determination of individual zone performance difficult. Lubell Oil Company is the principal operator in the field. Produced gas has a relatively low specific gravity (0.58–0.65) with no condensate. The Jefferson sandstone is the deepest producing formation in any of the gas pools of this report.

The gross upper Cromwell Sandstone is >125 ft thick in the study area, but most producing wells have <50 ft because of post-depositional erosion. Due to carbonate cementation and clay, the maximum amount of net sand is ~100 ft, and only a small fraction of this (usually <20 ft) occurs in producing wells. There is no net sandstone mapped in some producing wells because the reservoir has <8% porosity—the threshold used in the determination of net sandstone for this area. Originally, this was felt to be the lower limit necessary for significant gas production, but, in actuality, sandstone with porosity as low as 6–7% may be productive. There is good pressure communication within individual sandstone bars, but the bars and structures are isolated from each other. The Cromwell and Jefferson reservoirs are a little more than 4,100 ft deep in this field and consist chiefly of quartz grains with highly variable carbonate cement.

In about half of the Cromwell wells and most of the Jefferson wells, log shapes for discrete sandstone zones indicate coarsening upward textural profiles. This is best illustrated by the gamma-ray and resistivity logs in the field cross sections. The similar-shaped log patterns indicate a relatively simple depositional setting on a shallow marine shelf. Correlations within the Cromwell interval can be difficult, however, because of local stratigraphic changes caused by variations in sand supply, rates of deposition, accommodation space, structural movement contemporaneous with deposition, and post-depositional erosion.

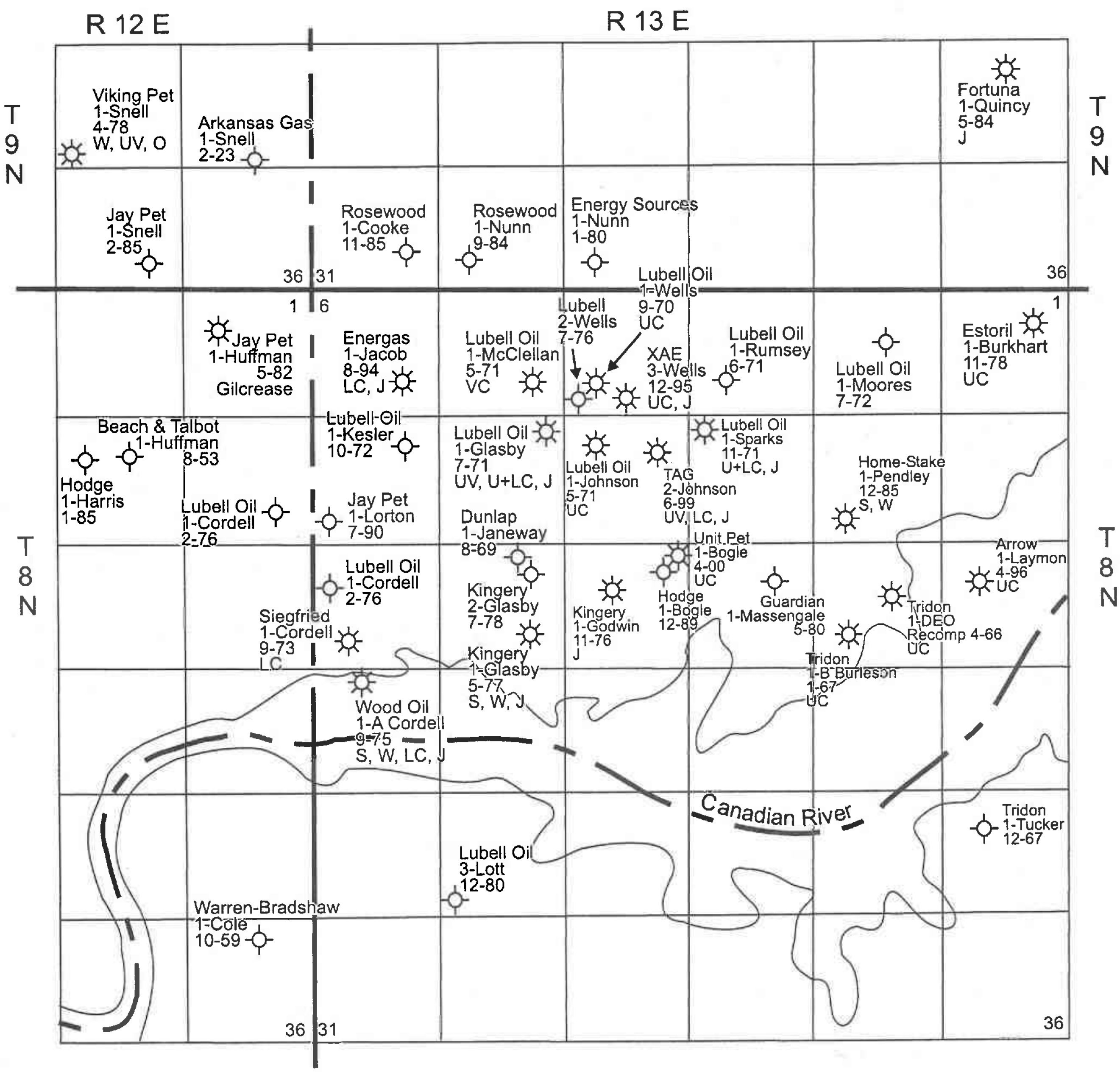
HISTORY OF DEVELOPMENT IN SCIPIO NW FIELD

The first well that penetrated the Cromwell in the study area was the Arkansas Gas Company well in sec. 25, T. 9 N., R. 12 E. It was drilled in 1923, tested dry, and there is no log available. A few other holes that were drilled in the 1950s and 1960s encountered thick Cromwell Sandstone but were also abandoned. Then in 1966, Tridon reentered a well previously drilled in 1955 by Public Service Company of Oklahoma and discovered a small three-well gas pool that eventually became part of Scipio NW Field. The Tridon well, located in the NE¼ sec. 14, T. 8 N., R. 13 E., was completed in the upper Cromwell and produced >1 BCFG. Four years later, in 1970, Lubell Oil discovered the main gas pool 3 mi to the northwest on a separate fault block. The Lubell well, the #1 Wells, is in the SW¼ sec. 4, T. 8 N., R. 13 E., and has produced 3 BCFG. Most of the other six wells drilled in the same area were drilled within a year, and two wells were drilled as late as 1995 and 1999. The later wells all found the reservoir pressure depleted. Additional small Jefferson sandstone discoveries were made in later years. In 1976, Kingery opened a small gas pool in the NW¼ sec. 16, and in 1975 Wood Oil found gas in the NW¼ sec 19. Figure 30 is a well information map identifying operators, well number and lease, and completion date of all the Cromwell penetrations.

STRATIGRAPHY

The Cromwell Sandstone is the lower Member of the Union Valley Formation. It usually is found divided into two sub-members, an upper and lower sandstone. Because the spatial distribution of the Cromwell Sandstone is highly variable in regards to thickness and composition, the two sub-members are often hard to distinguish on a regional basis. Both sub-members may contain multiple sandstone zones, or they may consist of a single massive sandstone, be replaced by shale, or even be absent due to erosion. The Jefferson sandstone lies beneath the Cromwell and is separated from it by the Springer shale. This unit is usually 10–30 ft thick and characterized by unusually low resistivity (high conductivity). The Jefferson is the equivalent of the Springer Cunningham sandstone of the Anadarko Basin. Low resistivity shale of the Goddard Formation underlies the Jefferson in this study area and has similar properties to that of the Springer shale.

The top of the Cromwell Member is often hard to identify. It is picked at the base of the overlying Union Valley Limestone, which is more easily determined from density-neutron logs as shown on the type well (Fig. 31). In that well, the Cromwell Sandstone has high porosity compared to the tight Union Valley Limestone. The accompanying PE log is even more diagnostic since quartz sandstone has values in the range of 2–3 and limestone has values of 3–5. In some places, however, this contact is gradational where the Cromwell Sandstone becomes limy or the Union Valley Limestone becomes sandy at its base. Resistivity, SP, and gamma-ray logs alone are not sufficiently definitive for picking this specific contact but can be useful in a general sense in distinguishing between the two members. Problematic picks of the Cromwell top also are seen on some logs in the regional and field cross sections.



Lubell Oil - Operator

1-Kesler - Well number and Lease

☼ 1-71 - Completion date

Producing reservoirs -
S = Spiro-Wapanucka
W = Wapanucka Limestone
UV = Union Valley Limestone
UC = Upper Cromwell Sandstone
LC = Lower Cromwell Sandstone
J = Jefferson sandstone
O = Other

Figure 30. Well information map showing operators, well numbers, lease names, producing reservoirs, and completion dates in Scipio NW Field, southwest McIntosh County.

The Union Valley Formation is comprised of the Cromwell Sandstone and the Union Valley Limestone which in turn is overlain by the Wapanucka Formation. The Wapanucka consists of a lower, relatively thick shale interval informally referred to as the Wapanucka shale or Limestone Gap shale, and an upper part consisting of a widespread limestone called the Wapanucka Limestone. Because of its regional extent, the Wapanucka Limestone is a useful datum for mapping structure (Pl. 3). The upper part of the Wapanucka Limestone grades into sandstone called the Spiro sandstone. A distinctive shale break several feet thick separates the upper Wapanucka Limestone and Spiro sandstone strata from a lower limestone sequence in the Wapanucka. This distinctive shale is used to define the top of the Wapanucka Limestone in the field structure map and cross sections. The overlying sand-

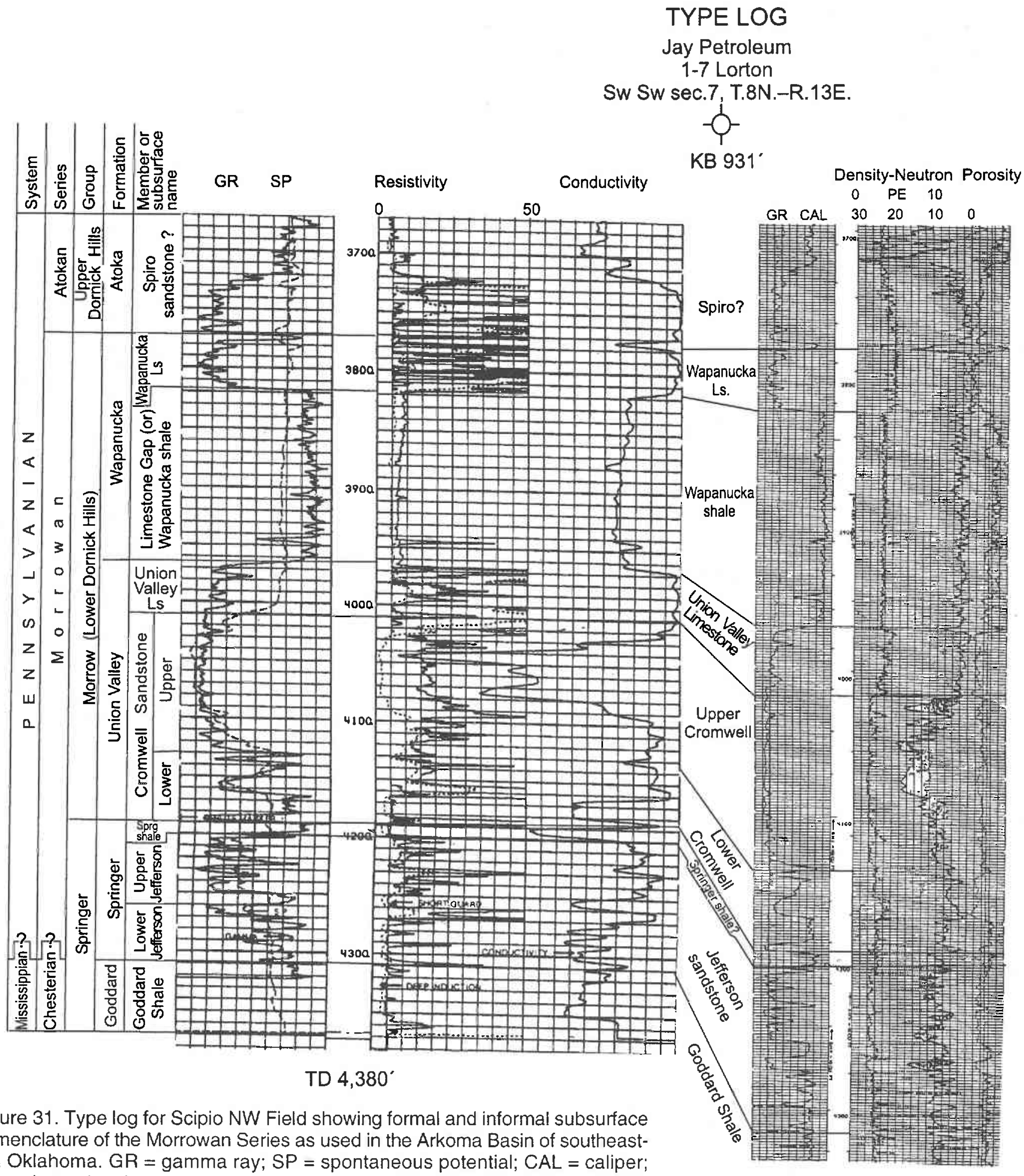


Figure 31. Type log for Scipio NW Field showing formal and informal subsurface nomenclature of the Morrowan Series as used in the Arkoma Basin of southeastern Oklahoma. GR = gamma ray; SP = spontaneous potential; CAL = caliper; PE = photo electric.

stone and limestone strata are simply referred to as Spiro/Wap in this study.

Cromwell Sandstone

In the Scipio NW Field type log (Fig. 31), the Cromwell Member (including shale) is ~180 ft thick and divided into upper and lower sub-members. A prominent shale break ~10 ft thick separates the two sandstone units. The upper Cromwell locally exceeds 125 ft and is usually comprised of two or three main sandstone zones. The lower Cromwell in the study area is generally thin and unimportant as a reservoir.

The distribution and reservoir characteristics of the upper Cromwell Sandstone are variable. Porosity reaches 14–18% in certain zones, but within a mile or less the same zone may become tightly cemented with carbonates, reducing its porosity to 3–4%. Low porosity makes it difficult to distinguish sandstone from limestone on logs. Additionally, an unconformity exists at the top of the upper Cromwell and erosion has removed all or part of that unit in some places. These local variations are often apparent where hydrocarbons are entrapped. Where productive, the upper Cromwell Sandstone always has a significant SP deflection, porosity >6%, and >25 ohm-meters (Ω) resistivity.

Sandstone intervals usually have a distinct coarsening upward textural profile on gamma-ray logs, but some zones have "blocky" textural profiles. The blocky log shape indicates a rapid transition from sandstone to shale at the lower and upper bed contacts. The relatively sharp contacts probably were influenced by storm-induced currents and rapid deposition in a shallow marine environment. Throughout the field, there is no evidence of fluvial channels in the Cromwell interval. Variations in log profiles represent different facies within or adjacent to bars deposited in the same marine environment. The bars in Scipio NW field area probably trended north to south, but post-depositional erosion has altered the original patterns of deposition.

Jefferson Sandstone

The Jefferson sandstone interval is particularly thick in Scipio NW Field. It contains two main sandstone zones, the upper being dominant and described here. Well logs indicate that the upper zone has multiple beds with an aggregate gross sandstone thickness of 30–50 ft. Individual beds are relatively persistent throughout the field with expected variations in thickness. In some places, they coalesce into one bar sequence, an indication that at least some beds are facies variations rather than unique depositional cycles. Most beds clearly have a coarsening upward textural profile as does the overall bed-set assemblage. This consistent textural pattern is characteristic of marine bars. These bars are oriented north to south, are normally 1–3 mi long, and generally <1 mi wide. They were not affected by the structural events that caused the erosion of the younger Cromwell.

The upper Jefferson sandstone locally has porosity of 6–12%, yet there are few good wells from this interval. Production is concentrated in structural highs along upthrown fault blocks and where net sandstone is the thickest. Like the Cromwell reservoirs, productive zones have porosity >7%, true resistivity (R_t) is >25 Ω, and the SP deflection is strong in regards to the bed thickness. Overall, the Jefferson in this study area is not a good reservoir, because sandstone zones are thin and permeability is probably low.

CROSS SECTIONS

The stratigraphy and structural details of the Union Valley Formation, specifically the Cromwell Sandstone Member, are shown on two detailed cross sections across Scipio NW Field. The selection of wells used in both sections was dictated by log quality, depth, and availability of gamma-ray and porosity logs. The upper part of each cross section is structurally controlled, and the lower part is a detailed stratigraphic reconstruction. Section A–A´ (Fig. 32, in envelope) is oriented north to south and shows Cromwell stratigraphy and the fault displacements in two gas pools in the field. Cross section B–B´ (Fig. 33, in envelope) shows the relationship of upper Cromwell production in Areas 1 and 2 and the nature of the downdip water leg in Area 1. Both stratigraphic cross sections use a common datum: the top of the Springer shale, which underlies the lower Cromwell Sandstone. The datum for both structural sections is mean sea level.

Cross Section A–A' (Figure 32)

This south-to-north section is comprised of five wells that show the nature of the unconformable surface overlying the Cromwell Sandstone and characteristics of two fault traps occurring in the field. In the Hodge well at location 1 (farthest south), the entire upper Cromwell Sandstone and the Union Valley Limestone are absent on an upthrown fault block. Displacement on the fault as shown in the top section is about 140 ft, and the amount of section removed due to erosion is approximately the same. The unconformable surface is interpreted to occur on top of the Cromwell Sandstone, whereas the absence of Union Valley Limestone appears to be related to nondeposition in this immediate area. In other areas within this field, the Union Valley Limestone is shown to overlie the eroded Cromwell. Because of the localized nature of the unconformity portrayed in this cross section, it is not shown on regional cross section C–C´ (Pl. 6). The Jefferson sandstone in the Hodge well is relatively thick and porous, but its low resistivity of only 15–30 Ω confirms that the sandstone is wet. Although this location is on the updip side of a fault, it is still structurally low to sandstone farther east.

The lower Cromwell, Jefferson, and Mississippian extend across the fault to location 2. At this location, the Unit Petroleum 1-Bogle well is located ~950 ft to the north, on the down side of the fault. There, the upper Cromwell Sandstone is 40 ft thick, has porosity of 12–14% in the lower half of the interval, and is structurally low to the main producing gas pool of Area 2. Resistivity in the porous lower part of the Cromwell Sandstone falls below 20 Ω, but when S_w calculations are run using 13–14% porosity, the zone calculates dry rather than wet. Resistivity up to 40 Ω in the upper part of the Cromwell occurs where the sandstone is relatively tight. The large density-neutron porosity crossover of as much as 16 porosity units probably indicates pressure depletion, a fact noted by test data included with the log. The well was completed in 2000, almost 30 years after the field was discovered. The Unit Petroleum well IPd at the rate of 661 MCFGPD, but after one year's production the cumulative total was negligible. The underlying Jefferson sandstone is unusually thick but is probably wet in the most porous part of the interval, since resistivity is <25 Ω.

The Tag Team well at location 3 is about eight-tenths of a mile farther north. Here, the Jefferson and Cromwell reservoirs are structurally lower, although thickening of the overlying Wapanucka shale causes the Wapanucka Limestone to be structurally higher. The Tag Team well encountered ~50 ft of upper Cromwell Sandstone and ~15 ft of lower Cromwell Sandstone. The upper Cromwell is very tight, and porosity logs indicate strata more like limestone rather than sandstone. Therefore, even though this interval was perforated, it is unlikely to produce much gas. The lower Cromwell was perforated in two thin zones, the lower of which appears to have local porosity development of ~8%. But since these reservoirs appear thin and laterally discontinuous, they too are likely to be poorly producing reservoirs. The underlying upper Jefferson sandstone contains two zones that appear to be the best reservoirs in the Tag Team well. Both zones are perforated where porosity varies between 6% and 12% and resistivity is >50 Ω. A third zone in the lower Jefferson appears to have minimal gas potential but also was perforated. Both upper Jefferson zones have large density-neutron cross-over, and initial test data indicates that the reservoirs were already pressure depleted. Confirming this, the well IPd for only 117 MCFGPD and had a BHP of only 530 PSI. The Tag Team well is a southwest offset to the Lubell well of location 4 and was completed in 1999—27 years after the Lubell well.

Four-tenths of a mile northeast of well 3, in the Lubell #1 Sparks well at location 4, the upper Cromwell thickens to 75 ft and is overlain by the Union Valley Limestone. The upper part of the upper Cromwell has porosity probably as high as 12–14%. The porosity log shows only density porosity, and in order to estimate true porosity it must be multiplied by some factor <1 (0.7) to account for gas effect. The lower part of the upper Cromwell is tight, as it is in the Tag Team well at location 3. The underlying Jefferson sandstone was perforated in three zones, but each is thinner than those at location 3. The Sparks well is one of the first drilled in the field and encountered nearly virgin reservoir pressure. It has produced almost 2.5 BCFG since being completed in 1972.

Another fault is crossed between wells 4 and 5. It has about 150 ft displacement and forms the trap for the gas accumulation in Area 1. At the fault boundary, the reservoir sandstones in the Cromwell and Jefferson intervals are displaced, up to the south, so that they are adjacent to the impervious Wapanucka shale or tight sections of the Union Valley Formation. In the Lubel well at location 5, the Upper Cromwell thickens to >80 ft thick but is wet or tight.

Logs of the Jefferson interval in the first four wells of this cross section show sandstone zones having coarsening upward textural profiles. This same textural pattern that is typical of marine bars happens in the lower and upper Cromwell Sandstone in well 4 and in the upper part of the upper Cromwell in well 5. The more abrupt basal contact of specific sandstone zones in the lower part of the upper Cromwell in wells 2 and 5 indicates that the bars have no transition zone and that sand probably was deposited more rapidly.

Cross Section B–B′ (Figure 33)

This west-to-east section shows conspicuous changes in the thickness of Cromwell Sandstone as a result of post-depositional erosion. The section also illustrates the nature of displacement along the main bounding fault that segregates gas pools in the south from those in the north. The structural portion of the cross section includes some of the stratigraphic section overlying the Union Valley Formation.

The log of the Jay Petroleum well at location 1 is used as the type section for the Morrowan in Scipio NW Field. In this well, the entire Union Valley Formation is present, including ~120 ft of upper Cromwell Sandstone and >20 ft lower Cromwell Sandstone. A fault is crossed ~0.6 mi to the northeast, and displacement on it is ~110 ft, up to the south. Where cross section A–A′ crosses the same fault 2.5 mi to the east, the displacement is ~120 ft.

At location 2, ~1.75 mi northeast of the fault, most of the upper Cromwell Sandstone is missing in the Lubell well, but the overlying Union Valley Limestone is intact. This relationship is evidence of an erosional unconformity predating deposition of the Union Valley Limestone. Since there are insignificant changes in the thickness or occurrence of strata immediately overlying the Union Valley LS (see upper section), it is unlikely that faulting is responsible for the large reduction in thickness of the Cromwell Sandstone. As represented by the SP and resistivity/conductivity log traces in the Lubell well, the upper Cromwell is only 50 ft thick and shows a coarsening upward sandstone profile. Intervals with resistivity >350 Ω in the zone of high SP deflection were perforated. The Lubell is the discovery well for the gas pool identified as Area 1 in this report. It produced >3 BCF gas between 1970 and its abandonment in 1979.

The lower part of the upper Cromwell thins to ~40 ft in the XAE well at location 3, ~0.25 mi to the northeast. There, the upper Cromwell Sandstone is distinguished by a 13-ft zone having ~13% porosity and as much as 14 porosity units of cross-over. These same characteristics are noted in the Unit well at location 2 on cross section A–A′. In both cases, the zones were pressure depleted: the initial shut-in pressure in the XAE well was only 205 PSI. The XAE well was drilled in 1995, 25 years after the pool discovery by Lubell Oil Company (well 2 in section B–B′). The underlying Jefferson sandstone probably is producing most of the gas in the XAE well since that reservoir was not depleted. The Jefferson is productive from two zones having porosity of 7–8%.

About 2 mi southeast at location 4, the full upper part of the upper Cromwell is present in the Home Stake well. That location is structurally low to producing wells in the field and most sandstone zones in the Cromwell have low porosity and calculate wet. At least two zones in the Cromwell and one in the upper Jefferson have relatively low calculated water saturations (S_w) but apparently tested dry following perforation.

The PSC well at location 5 is the easternmost well in cross section B–B´. It was originally abandoned but later reentered and completed as a gas discovery in a small accumulation trapped by the same fault described between locations 1 and 2. The fault is about half way between locations 4 and 5 and strikes east–west with throw to the south of ~120 ft. As shown by the resistivity log, an apparent gas/water contact occurs below ~4,210 ft where the resistivity drops from ~20 Ω to <5 Ω. The presence of a gas/water contact severely limits the size of this gas pool. Initial pressure in the PSC well was 1,750 PSI, which is typical for normal pressured reservoirs in this part of the Cromwell play.

STRUCTURE
(Figure 34)

Scipio NW Field is in the central part of the Arkoma Basin where severe structural deformation is relatively minor. Even so, small faults provide trapping mecha-

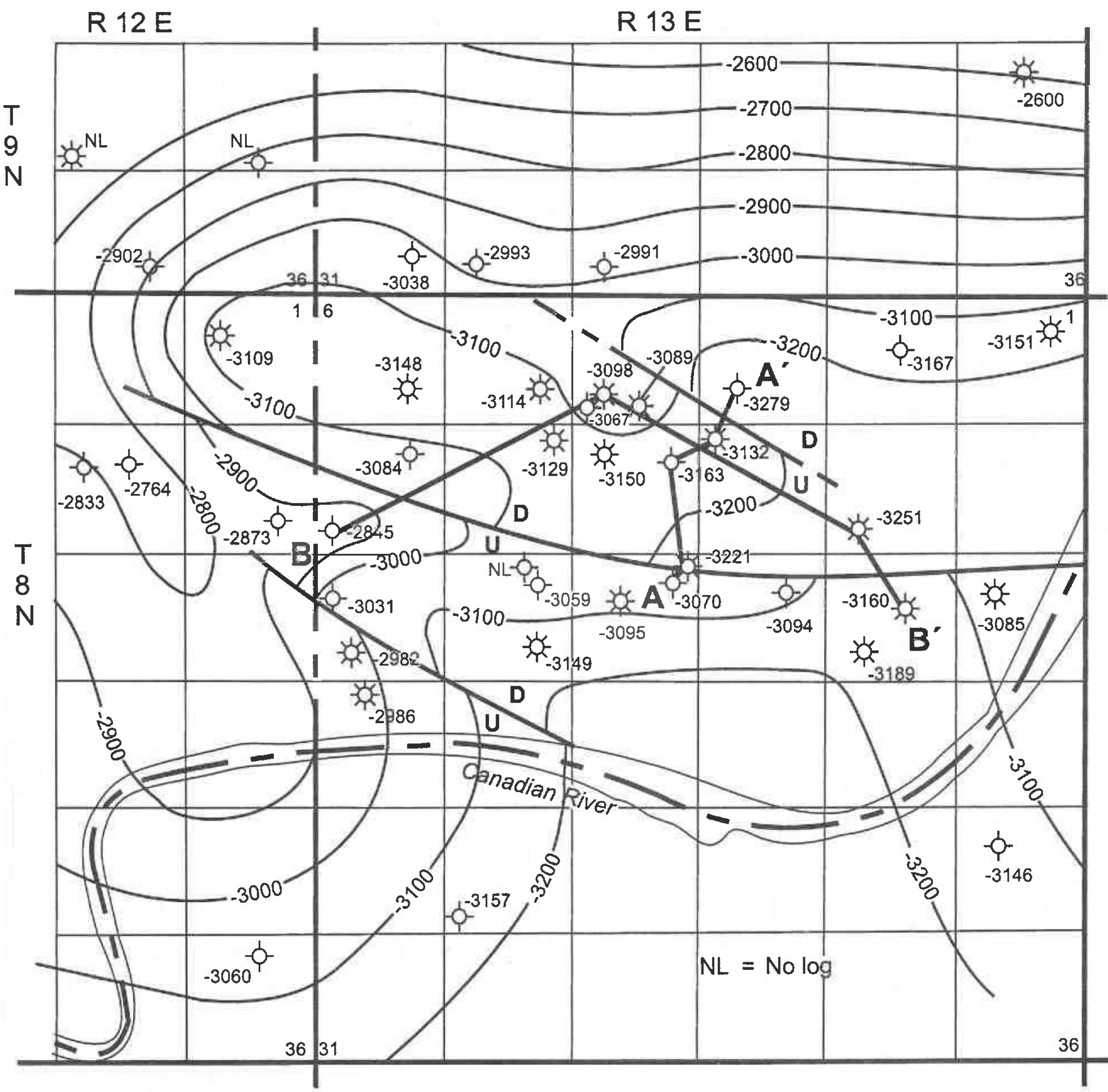


Figure 34. Structure map depicting the top of the Wapanucka Limestone, Scipio NW Field, southwest McIntosh County. Contour interval is 100 ft. Datum is mean sea level. See Figure 30 for well names.

nisms for the gas pools that comprise this field. These smaller faults are not represented in the regional structural maps of Plate 5. None of the faults in this study area have formal recognized names, but they may extend several miles east to west. They have maximum throws of ~150 ft, and displacement is up to the south in all cases. The structure map of the Scipio NW area (Fig. 34) shows the configuration of the top of the Wapanucka Limestone (see type log, Fig. 31). The top of the "Wap" is about 300 ft above the top of the Cromwell and accurately represents the structure of both units. The Union Valley Limestone or Cromwell cannot be used as structural data because they are locally absent.

The structurally high parts of the four gas pools are immediately south of the trapping faults, on the upthrown side. Potential reservoirs on the north, downthrown, side of the faults are wet. The subsea of the "Wap" in the northern gas pool, Area 1, is between –3,100 ft and –3,200 ft, whereas the subsea of the "Wap" in the southernmost producing area is between –2,900 and –3,000 ft. This is a reversal of regional, basinward dip.

SANDSTONE DISTRIBUTION AND DEPOSITIONAL ENVIRONMENTS

The two principal reservoirs in Scipio NW Field are the upper Cromwell Sandstone and the Jefferson sandstone. Isopach maps depicting the gross and net sandstone thicknesses of these reservoirs are included in Figures 35, 36, 37, and 38.

Upper Cromwell Sandstone (Figures 35 and 36)

Figure 35 shows the gross thickness of the upper Cromwell Sandstone for all the wells in the study area. That value was determined from the 50% sand/shale line on the gamma-ray logs and does not include shale intervals.

Gas production in the Cromwell is not controlled by the gross sandstone thickness. In fact, better Cromwell production generally occurs where the sandstone is *thinnest*. This occurs because much of the sandstone is eroded from uplifted fault blocks leaving only the lowermost part of the Cromwell intact. Because the gross sandstone map is based on actual sandstone thickness and is independent of porosity, it is often the map of choice in depicting bar geometry. However, because so much of the Cromwell Sandstone is eroded in this study area, the map cannot be used for this purpose.

The gross upper Cromwell Sandstone is >100 ft thick northeast of the field and >125 ft thick to the southwest. But in the intervening area where gas production occurs, the sandstone thins to <50 ft and is actually absent along a narrow zone parallel to the fault blocks. The decrease in the amount of upper Cromwell sandstone provides a stratigraphic trapping component along the northwest side of producing Area 1.

Textural patterns (from well logs) and sedimentary structures (from core and outcrops) are the principal lines of evidence for these reservoirs being marine bars. Both features have characteristics that are influenced by depositional processes consistent in a shallow marine environment. For textural log patterns, the nature of the *lower* bar contact often is diagnostic: some bars have gradational lower contacts, whereas other contacts are more abrupt. The explanation is that gradational contacts grade upward from shale at the base to sandstone above and were formed during slow vertical accretion. This textural pattern may indicate that deposition took place in deeper water farther basinward or that it occurred adjacent to the main bar complex. More abrupt basal contacts probably are indicative of rapid bar deposition since there is little development of a transition zone. These types of basal bar contacts are more likely to form closer to shore in a sand-rich marine environment where high current energy exists. Both kinds of lower bar contacts characterize the Cromwell and are shown on log traces in cross sections A–A′ and B–B′ (Figs. 32, 33).

Sedimentary structures are also diagnostic of specific depositional environments and are often correlative to certain bar zones identified from well logs. Scoured bedsets, massive, convolute, high-angle cross bedding, and beds containing transported fossil fragments typically are found in the upper part of a marine bar sequence typically represented by a "clean" gamma-ray log signature. These facies are indicative of shallow, high-energy environments where deposition is rapid. Other sedimentary structures are common to the Cromwell but originate in a very different marine environment. Ripple bedding, bioturbation, and abundant trace fossils are commonly found in bar transition and lower bar facies that typically are represented by a transitional gamma-ray log signature beneath the upper bar facies. These facies generally indicate slower, more uniform, non-destructive, and in some situations, slightly deeper water deposition.

Figure 36 shows the thickness of net upper Cromwell Sandstone having porosity ≥8% for all wells in the study area. This porosity value was *initially* judged to be the lower limit necessary for significant gas production in Scipio NW Field. Now, it is thought that sandstone having porosity as low as 6–7% contributes gas reserves but exponentially in smaller gas volumes. Porosity values were determined by visually averaging the cross-plot porosity on density-neutron logs. No adjustments were made to account for logs recording porosity based on a limestone or limy sandstone matrix (density of 2.71 and 2.68 g/cm^3, respectively). In the absence of a neutron log, density-porosity determinations were made by multiplying the observed density porosity by a factor of <1.0 (usually ~0.7) to account for the gas effect on the density log. In producing Cromwell wells, the mapped net sand thickness generally ranges from 15 to 40 ft, but four producing wells in Area 1 are mapped with no net sandstone. In those wells, the porosity falls below the 8% cutoff limit initially established during log evaluation. Apparently a net sandstone cutoff of 6% would be more realistic and is recommended in the future. The average thickness of productive net sandstone is probably a little more than 10 ft.

The net and gross sand isopach maps (Figs. 35, 36) are similar in overall appearance, but the net map shows a significant reduction in sandstone thickness. This reduction is due mainly to diagenetic alteration of sandstone,

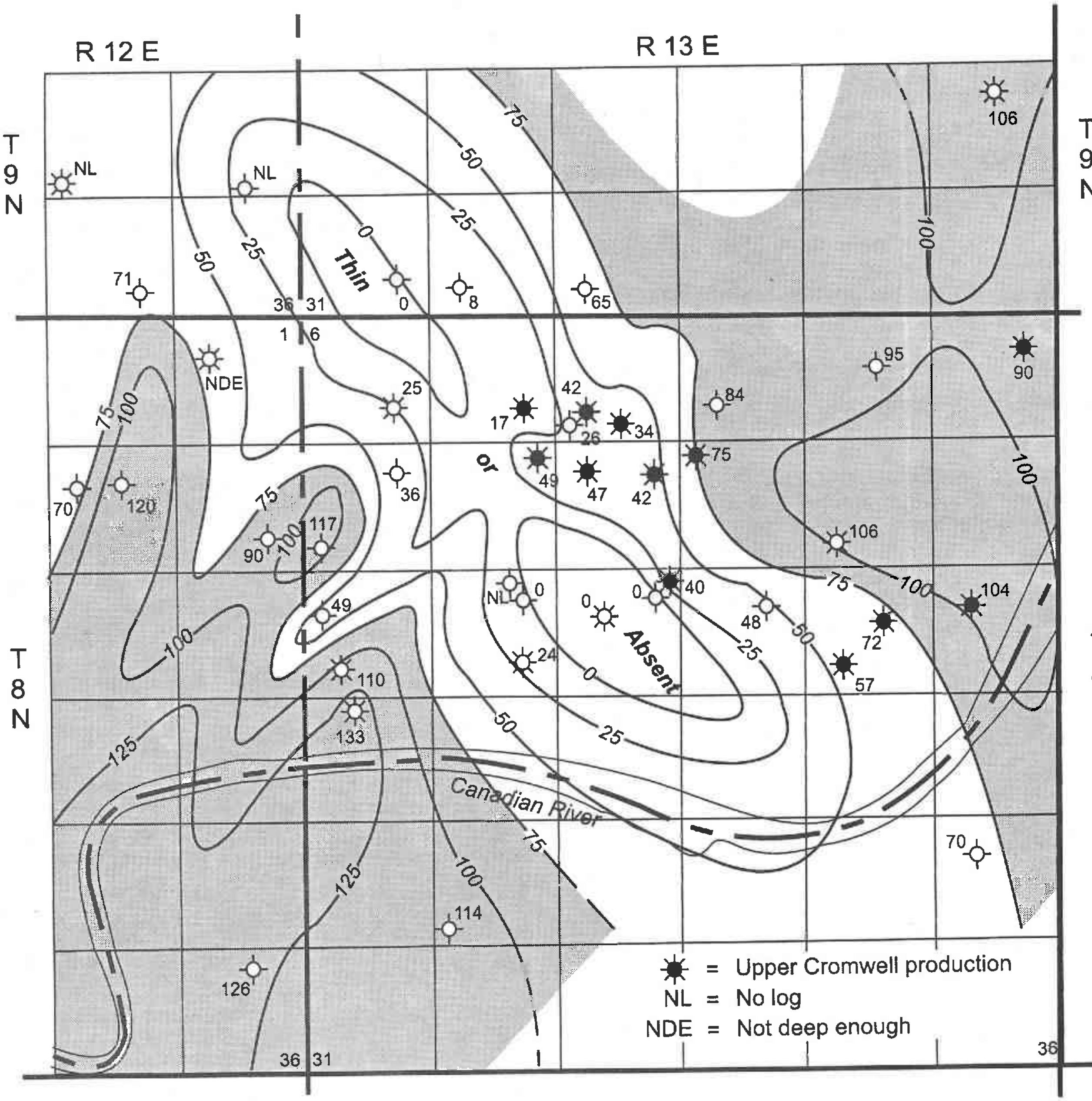


Figure 35. Gross isopach map of the upper Cromwell Sandstone in Scipio NW Field. Contour interval is 25 ft. See Figure 30 for well names.

causing it to be tightly cemented with carbonate material. Cementation locally reduces the net sandstone thickness by a factor of >50%, and in some wells there is *no* effective porosity. The net/gross sandstone relationship can be seen by comparing the gamma-ray and porosity responses on any of the logs in cross sections A–A′ and B–B′ (Figs. 32, 33). Sandstone generally has porosity in the range of 5–14%, but a few wells have zones with porosity >18%. These highly porous zones commonly are found within thick sequences of Cromwell Sandstone and probably indicate different depositional episodes.

The upper Cromwell Sandstone is productive in both Areas 1 and 2 as shown on the generalized location map (Fig. 28). Both areas extend laterally along the south, upthrown side of faults depicted on the net sandstone map (Fig. 36). Three of the seven wells in Area 1 produce entirely from the upper Cromwell, and four have production commingled with that of the lower Cromwell, Jefferson, and the Union Valley Limestone. Most of the gas produced in commingled wells is attributed to the upper Cromwell reservoir. Three wells in Area 2 produce gas entirely from the upper Cromwell. Early wells that encountered near virgin reservoir pressure will produce >3 BCFG, whereas pressure-depleted wells in both areas produce much less.

There appears to be a gas/water contact along the southwest edge of production in Area 2 (sec. 14, T. 8 N., R. 13 E.) as noted on the net sandstone map (Fig. 36). It

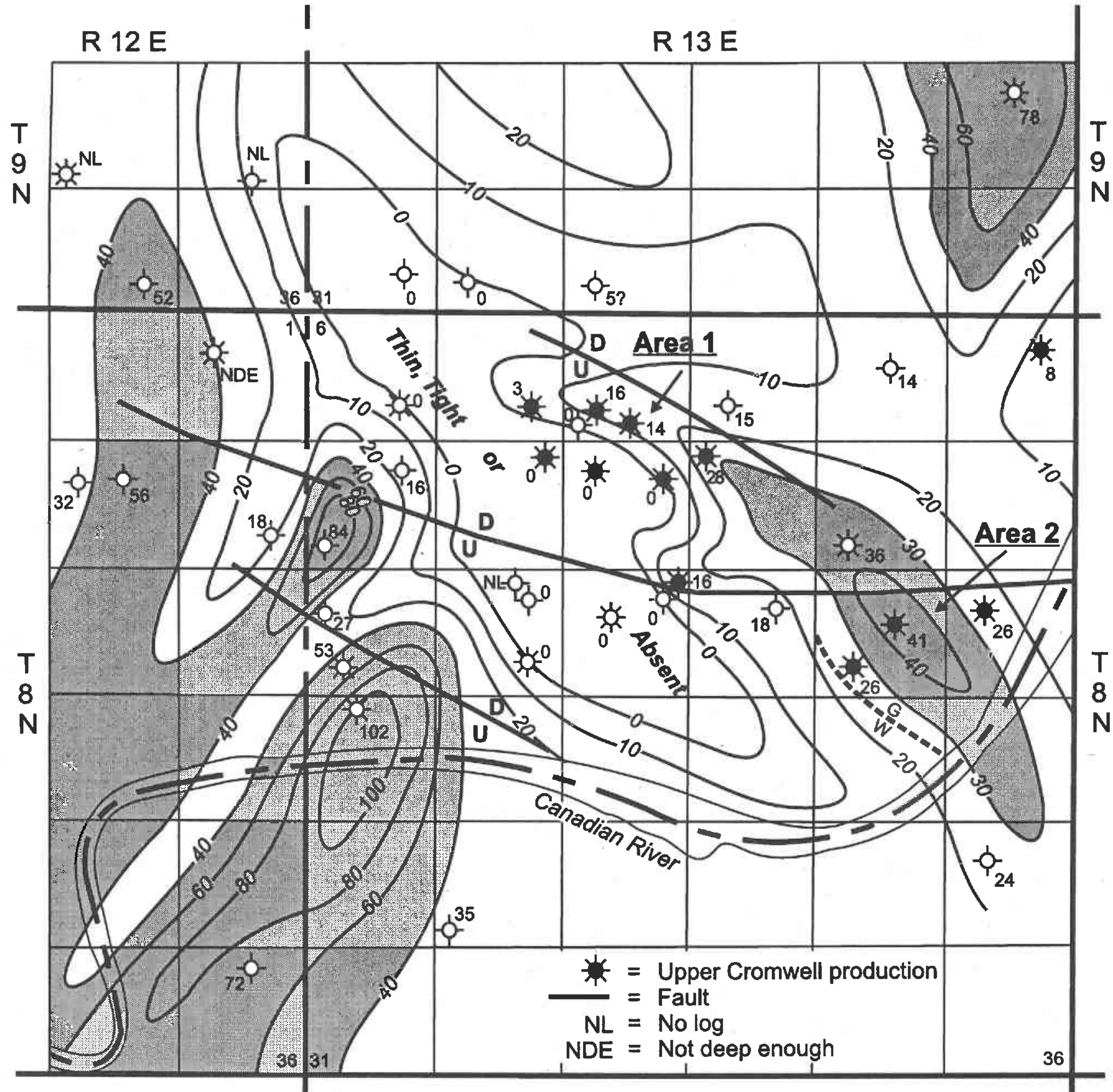


Figure 36. Net isopach map of the upper Cromwell Sandstone in Scipio NW Field. Net sandstone has log porosity ≥8%. Contour interval is 20 ft except in producing areas where it is 10 ft. See Figure 30 for well names.

occurs at 4,210 ft in the #1-B Burleson well at location 5 in cross section B–B´ (Fig. 33). There may also be a gas/water contact in the southeast part of sec. 10 of Area 1, but it is not apparent on the log of the well in sec. 16, location 2, of cross section A–A´.

It is thought that during Cromwell time, sand was transported into the Arkoma Basin via incised channel systems originating from the west. Sand was carried many miles across a shallow marine shelf environment and deposited in north-trending bars that comprise this field study area. Water depth was perhaps only 25–50 ft. As the amount of sand diminished eastward away from supply corridors, the thickness of bars became progressively thinner.

Upper Jefferson Sandstone (Figures 37 and 38)

Figure 37 shows the gross sandstone thickness in the upper Jefferson interval as defined on the type log of the Jay Petroleum #1-7 Lorton well (Fig. 31) and location 1 of cross section B–B´ (Fig. 33). This interval includes the total thickness of sandstone regardless of porosity as interpreted from gamma-ray logs (determined from the 50% sand/shale line) and does not include interbedded shale. The Jefferson commonly has two or more sandstone zones that split and coalesce, indicating changing depositional conditions and bar facies. A gross thickness of

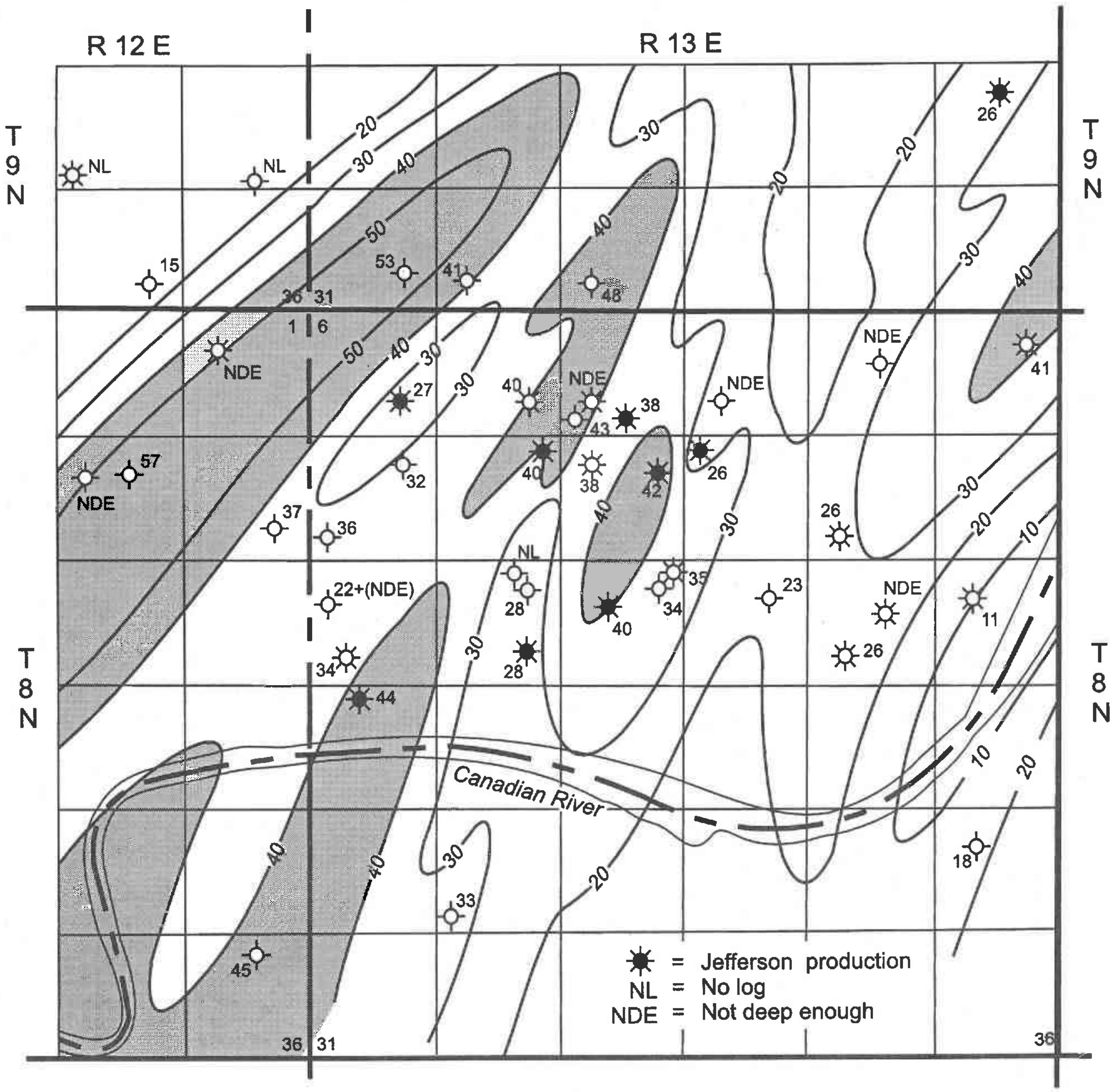


Figure 37. Gross isopach map of the upper Jefferson sandstone interval in Scipio NW Field. Contour interval is 10 ft. See Figure 30 for well names.

40–50 ft is common, not including the lowermost sandstone zone, which may contribute another 10 ft. The Jefferson bars are easily recognizable on the isopach map; they extend for several miles in a north–northeast direction but are only ~1 mi wide. Interbar facies consist of shale or thinly bedded sandstone and shale. The thickest accumulation of Jefferson sandstone appears to be in the northwest half of the study area.

Like the Cromwell, the Jefferson sandstone was deposited in an offshore marine environment. This interpretation is based on gamma-ray log profiles, areal distribution patterns and sequence stratigraphic relationships. The sandstone interval is comprised of a series of stacked, shallow marine, detached bar sequences. All bar sequences are encapsulated by marine shale and have no associated deposits of deltaic origin. Individual bars or sandstone ridges persist throughout the study area but locally coalesce to form a single, thicker bar complex. This is illustrated between wells 3 and 4, cross section A–A′ (Fig. 32).

Almost every Jefferson sandstone sequence has a coarsening-upward textural profile and sharp upper contact with shale. Marine shale lies above, beneath, and laterally from the sandstone. In most of the bars, the cleanest sandstone and highest porosity occurs in the upper part of the bar. But in some of the thicker Jefferson sandstone sequences, the best porosity develops slightly below the bar top which is tight because of secondary carbonate cement.

The net isopach map of the upper Jefferson sandstone (Fig. 38) shows the thickness of sandstone having porosity ≥8%. Porosity values were determined by visually aver-

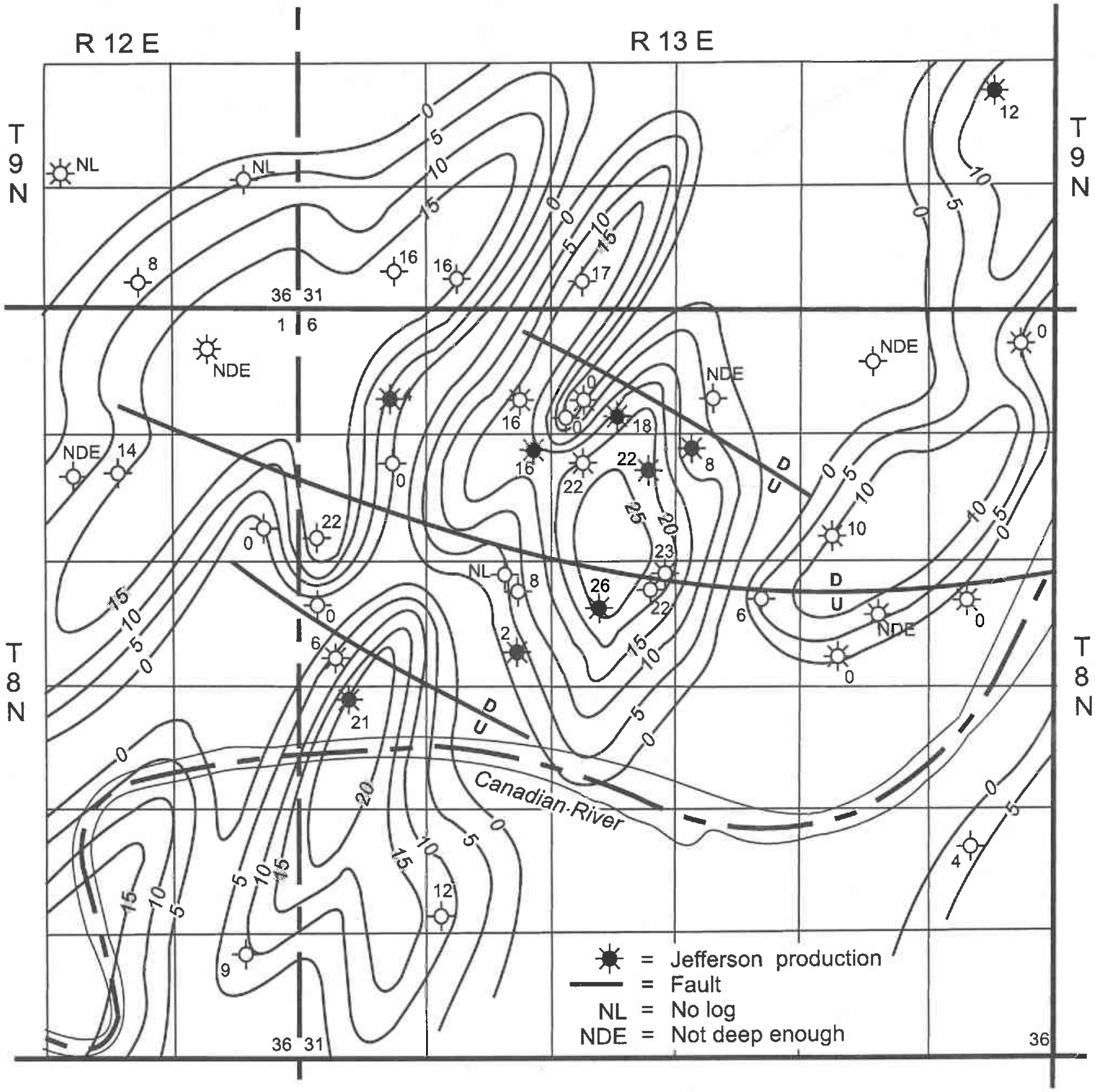


Figure 38. Net isopach map of the upper Jefferson sandstone interval in Scipio NW Field. Net sandstone has log porosity ≥8%. Contour interval is 5 ft. See Figure 30 for well names.

aging the cross-plot porosity on density-neutron logs. No adjustments were made to account for logs recording porosity based on a limestone or limy sandstone matrix (density of 2.71 and 2.68 g/cm^3, respectively). Density-porosity determinations in the absence of a neutron log were made by multiplying the observed density porosity by a factor <1.0 (usually ~0.7) to account for the gas effect on the density log. In wells producing from the Jefferson, the net sand thickness ranges from only a few feet to 26 ft and averages about 16 ft.

The spatial distribution of net sandstone shown on the isopach map (Fig. 38) is roughly the same as that of the gross sandstone (Fig. 37), even though the two maps look vastly different. This happens because the net sandstone map uses a smaller contour interval to portray a multitude of stratigraphic compartments. Each compartment has finite limits, meaning they "zero out," and the aggregate of these compartments do not necessarily conform to the gross bar outlines. The faults are the principle trapping mechanisms in the Jefferson reservoirs, but they do not affect distribution trends of this sandstone. Irregularities in permeability and porosity most importantly complicate production tendencies of this reservoir. To portray the relationship of structure, net sandstone, and production allocation, the three bounding faults are shown on the net sandstone isopach of Figure 38.

Differences between the gross and net sandstone thicknesses seem to be greater in the Jefferson sandstone than in the overlying Cromwell. Many wells with 20–30 ft of gross Jefferson sandstone have little or no net sandstone. In wells that do produce from the Jefferson sandstone, porosity may be as high as 12% but is usually in the range of only 6–8%. This is comparable to that of the Cromwell, yet Jefferson wells do not normally produce much gas in this area. This is probably due to lower permeability and restricted reservoir continuity in the Jefferson sandstone.

Each Jefferson producing area is on an upthrown block immediately south of a fault. Jefferson production is commingled with gas from other zones in all but one well, so it is difficult to judge production characterizes of the Jefferson reservoir by itself. In most wells, the Jefferson seems be a reservoir that will produce about one-fourth to one-third BCFG per well.

CORE ANALYSIS

There are no core analyses available from either the Cromwell or Jefferson wells in Scipio NW Field. Several core analyses of the Cromwell Sandstone are available from Deep Rock wells 20 mi to the west in Ts. 6–7 N., R. 10 E. (Figs. 22, 23 [Part I]). Those analyses indicate that sandstone with porosity of 10% has permeability between 1 and 10 millidarcies (md). Sandstone with porosity of 14% has permeability of 20 to >100 md. These values are probably applicable to the Upper Cromwell Sandstone in Scipio NW Field.

FORMATION EVALUATION

Correlation of the upper Cromwell Sandstone in Scipio NW Field can be troubling owing to rapid changes in porosity and large variations in thickness due to erosion. In the underlying Jefferson interval, however, sandstone zones are relatively persistent and easy to correlate. Therefore, data used in reservoir evaluation of the Jefferson such as sandstone thickness, porosity, water resistivity, and formation resistivity are all factors that are easily determined and applicable to a specific zone. This same reservoir data may have inconsistencies when portraying Cromwell sub-members, and this will affect calculations of gas reserves, water saturation, and reservoir limits. Interstitial clay does not seem to interfere with calculations or determining reservoir parameters for either the Cromwell or Jefferson.

Cromwell Sandstone is typically very clean except for the ubiquitous carbonate and silicate cementation. This is apparent on gamma-ray logs by the low response across sandstone intervals. In the absence of significant formation clay, values of true formation resistivity (R_t) taken directly from well logs leads to plausible calculated water saturation (S_w) values in most reservoir conditions, whether water-wet or hydrocarbon-saturated. Notation of R_w values sometimes were indicated on logs from service company calculations, although their value of 0.04 ohm-meters (Ω) resulted in S_w values that were consistently too high. Experimentation with different R_w values was necessary to more realistically characterize water-wet and hydrocarbon zones. Finally, an R_w of 0.03 Ω was decided upon, which resulted in relatively realistic values of S_w when considering both saturated and wet zones.

The deep, or true, resistivity (R_t) of producing sandstone in the Cromwell Formation typically ranges from 30 Ω to a little more than 200 Ω. A deep resistivity of <25 Ω almost always indicates that the zone is wet unless porosity is anomalously high or the reservoir is depleted. With a typical porosity of 6–8%, the Cromwell probably won't produce significant gas if there is <40 Ω resistivity. On the other hand, extremely high resistivity in excess of 100 Ω, in the absence of net porosity, indicates the formation is tightly cemented.

Characterization of permeability and porosity by examining the separation between the shallow and deep resistivity curves seems to be an effective technique of quickly interpreting sandstone quality for both the Cromwell and Jefferson sandstone. This method is based on the assumption that the amount of invasion of drilling fluids is proportional to the porosity and permeability of the reservoir, and that the amount of separation between the shallow- and deep-resistivity curves is affected by the degree of invasion. The Cromwell consistently shows good resistivity separation in porous zones, whereas it does not generally happen for the Jefferson. This may explain why most Jefferson zones are not highly productive despite having good porosity. Porosity separation is best determined from the detailed resistivity log, which is not included in the field cross sections.

Porosity determinations were made by taking the cross-plot porosity of the density-neutron logs. Porosity values in the "cleanest" part of the producing Cromwell Sandstone intervals range from 4% to 14% and average about 6–8%. Porosity in the Jefferson sandstone ranges from 5% to 12% and averages ~7%. Logging companies routinely combine density-neutron tools and compute porosity using a matrix density of 2.71 g/cm^3 (limestone) or 2.68 g/cm^3 (limy sandstone). Deriving porosity using the higher matrix density (2.71) theoretically results in values a few percentage points too high, whereas using the lower matrix density (2.68) results in more-accurate porosity values. This occurs because most Cromwell and Jefferson sandstone has carbonate cement. Porosity values used in this study were pessimistically estimated to take into account a limestone matrix density (2.71) but were not reduced by two to three percentage points as some log analysts do. When only density porosity was available, values were reduced by multiplying the indicated density porosity by a fraction, usually ~0.7, so that the resulting porosity accounts for some of the normal gas effect in producing wells that causes the density porosity to be too high. Gas effect (crossover) in productive intervals is consistently 5–10 porosity units but may be much less in sandstone zones that are tight. Extremely large separations of 14–15 porosity units are thought to be due to pressure depletion.

Water-saturation (S_w) calculations for the Cromwell and Jefferson are extremely variable and range from <10% to >100% (Table 3). In producing zones, calculations normally show S_w being <40%, although some producing zones are difficult to evaluate and may have S_w in excess of 50%. In these situations, S_w values are probably correct but include water bound in shale rather than free (mobile) water in sandstone. Similarly, cementation is blamed for unrealistically high S_w values in tight zones, because the

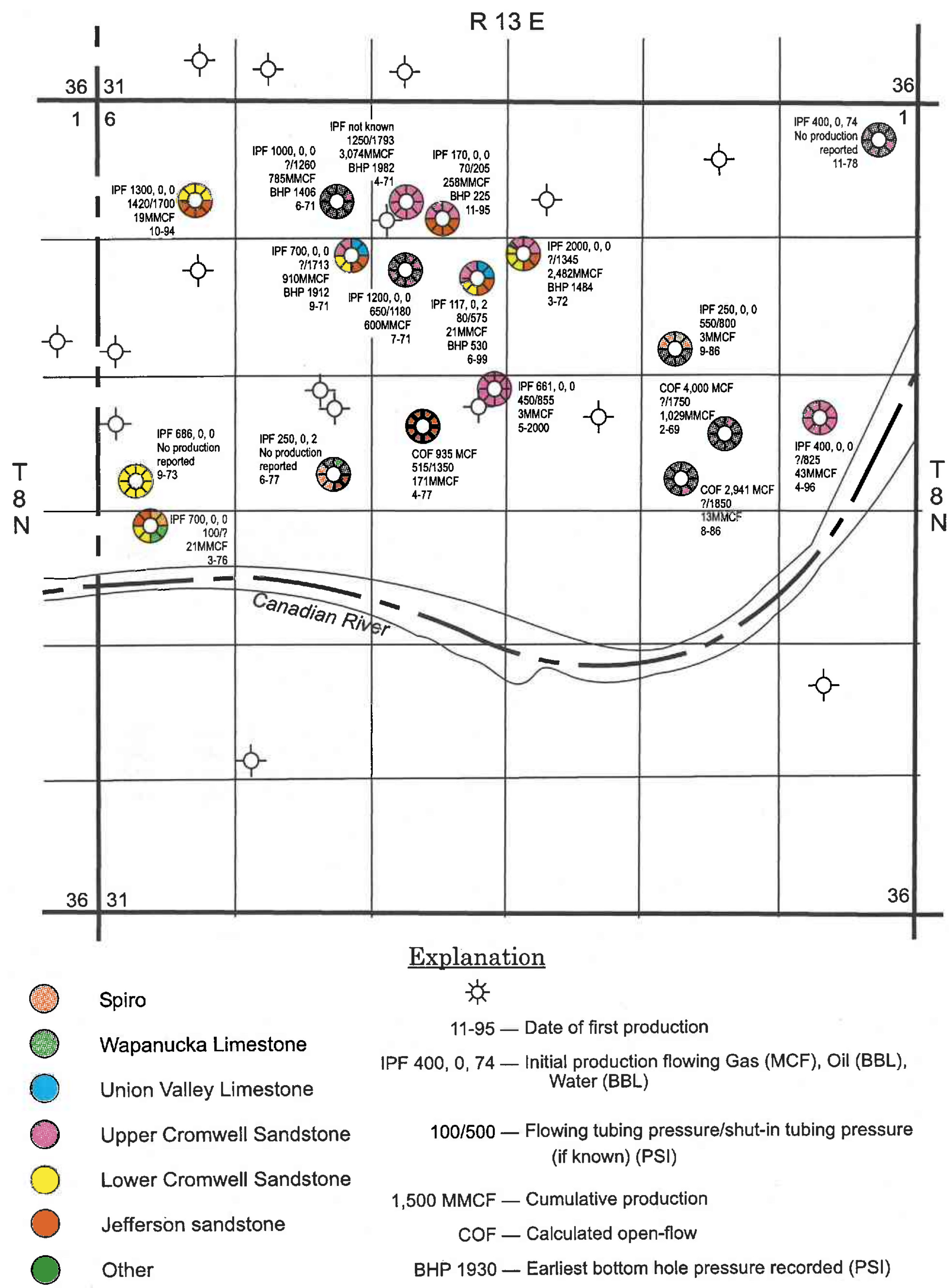


Figure 39. Reservoir information map of Scipio NW Field showing producing reservoir, date of first production, initial production (IP), flowing and shut-in tubing pressure (FTP, SITP), and cumulative production through June 2002.

TABLE 3. — Well Information Sheet Identifying Formation Tops and Sandstone Thickness,

S3	S2	S1	SEC	Status	Operator	Lease	Well #	Comp date	ELEV	TD	Perforated interval	Wapanucka Limestone top	Wapanucka Limestone subsea	Union Valley Limestone top	Union Valley Limestone subsea	Cromwell Upper and Lower net 8%	Cromwell Upper and Lower gross
				W=Wapanucka; UV=Union Valley; UC=Upper Cromwell; LC=Lower Cromwell; J=Jeferson													
T. 8 N., R. 12 E.																	
	s/2	Nw	1		Jay Petroleum	Huffman	1	May-82	797	3860		3906	-3109	nde			
	s/2	Nw	11	dry	Hodge	Harris	1	Jan-85	877	4107		3710	-2833	3858	-2981	32	70
	Sw	Ne	11	dry	Beach & Talbot	Huffman	1	Aug-53	890	5025		3654	-2764	3796	-2906	56	136
	C	Se	12	dry	Lubell Oil	Cordell	1	Feb-76	912	4281		3785	-2873	3947	-3035	18	151
	Ne	Se	34	dry	Bailey Pet		1	Nov-86	737	5060		3846	-3109	4014	-3277	41	158
	Nw	Ne	36	dry	Warren-Bradshaw	Cole	1	Oct-59	760	5935		3820	-3060	3970	-3210	72	140
T. 8 N., R. 13 E.																	
	Ne	Ne	1		Estorii	Burkhart	1	Nov-78	700	4410	4104-18; 4128-40	3851	-3151	4054	-3354	8	105
	Sw	Ne	2	dry	Lubell Oil	Moores	1	Jul-72	737	4298		3904	-3167	4148	-3411	14	95
	C	Sw	3	dry	Lubell Oil	Rumsey	1	Jun-71	714	4478		3993	-3279	4298	-3584	15	89
	Sw	Se	4		XAE Corp	Wells	3	Dec-95	713	4300	4138-50; 4217-24, 4268-74	3802	-3089	4104	-3391	28	44
	C	Sw	4		Lubell Oil	Wells	1	Sep-70	714	4222	4120-22; 4129-36	3812	-3098	4082	-3368	16	52
	Sw	Sw	4	dry	Lubell Oil	Wells	2	Jul-76	716	6100		3783	-3067	4076	-3360	0	26
	C	Se	5		Lubell Oil	McClellan	1	May-71	736	4390	4257-61	3910	-3114	4211	-3415	3	20
	Nw	Se	6		Energas	Jacob	1	Aug-94	774	4496	4300-04; 4364-71; 4390-96	3922	-3148	4206	-3432	9	51
	Sw	Sw	7	dry	Jay Pet	Lorton	1	Jul-90	931	4380		3776	-2845	3966	-3035	84	139
	C	Ne	7	dry	Lubell Oil	Keasler	1	Oct-72	824	4429		3908	-3084	4185	-3361	16	54
	C	Ne	8		Lubell Oil	Glasby	1	Jul-71	855	4493	4293-4356; 4386-4465	3984	-3129	4290	-3435	0	54
	S/2	Ne	9	gas, W, UC, LC, J	Tag Team Resources	Johnson	2	Jun-99	733	4429	4242-4378	3896	-3163	4216	-3483	13	60
	C	Nw	9		Lubell Oil	Johnson	1	May-71	808	4481	4333-41	3958	-3150	4268	-3460	0	51
	Nw	Nw	10		Lubell Oil	Sparks	1	Nov-71	715	4366	4167-89; 4226-27; 67-68; 92-93; 4303-11; 20-27	3847	-3132	4153	-3438	28	83
	Se	Sw	11		Home Stake	Pendley	1	Dec-85	719	4650		3970	-3251	4272	-3553	48	110
	Se	Nw	13		Arrow Oil	Layman	1	Apr-96	875	4486	4226-30	3960	-3085	4190	-3315	26	117
	Ne	Sw	14		Tridon Production	Burelson	1	Jan-67	659	5200	4180-86	3848	-3189	4158	-3499	26	62
	Sw	Ne	14		Pub Serv Co. of OK	DEO	1		673	4236	4180-83	3833	-3160	4137	-3464	41	72
	Sw	Ne	15	dry	Guardian & DFW	Massengale	1	Jun-80	742	4400		3836	-3094	4140	-3398	18	58
Sw	Ne	Ne	16	dry	Hodge	Bogle	1	Dec-89	721	4400		3791	-3070	absent		0	2
Ne	Ne	Ne	16		Unit Pet	Bogle	1	Apr-00	599	4320		3820	-3221	absent		16	45
	Se	Nw	16		Kingery Drilling Co.	Godwin	1	Nov-76	879	4423	4294-99, 4308-24	3974	-3095	4212	-3333	0	2
	C	Se	17		Kingery Drilling Co.	Glasby	1	Jun-77	667	4350	3760-3840; 4300-10	3816	-3149	4111	-3444	0	46
	C	Ne	17	dry	Kingery Drilling Co.	Glasby	2	Jul-78	897	4402		3956	-3059	4271	-3374	0	19
	Nw	Ne	17	dry	Dunlap	Janeway	1	Aug-69		4360		nl		nl		nl	nl
	C	Sw	18		Siegfried	Cordell	1	Sep-73	698	5119	4089-93	3680	-2982	3864	-3166	178	165
	Sw	Nw	18	dry	Lubell Oil	Cordell	1	Feb-76	819	4253		3850	-3031	4050	-3231	27	57
	Ne	Nw	19		Wood Oil	Cordell	1-A	Sep-75	672	4240		3658	-2986	3844	-3172	165	171
	Se	Nw	25	dry	Tridon	Tucker	1	Dec-67	750	5665		3896	-3146	4240	-3490	24	85
	Sw	Sw	29	dry	Lubell Oil	Lott	3	Dec-80	962	4674		4119	-3157	4297	-3335	35	121
T. 9 N., R. 12 E.																	
	Sw	Se	25	dry		Snell	1	Feb-23		4045		nl		nl			
	Sw	Sw	26		Viking Pet	Snell	1	Apr-78	842	4100		nl		nl			
	Nw	Ne	33		C & S Exploration	Snell	1	Nov-79	791	3900		3346	-2555	3483	-2692		
	C	Se	35	dry	Jay Pet	Snell	1	Feb-85	788	4451		3690	-2902	3862	-3074	52	71
T. 9 N., R. 13 E.																	
	C	N/2	25		Fortuna Energy	Quincy	1	May-84	736	4693		3336	-2600	3550	-2814	78	106
	C	Se	31	dry		Cooke	1	Nov-85	722	4196		3760	-3038	3926	-3204	0	12
	C	Sw	32	dry		Nunn	1	Sep-84	725	4220		3718	-2993	4006	-3281	0	10
	C	Sw	33	dry	Energy Sources	Nunn	1	Jan-80	694	4200		5	71	8054	-6666	5	71

Note: Highlighted rows indicate Cromwell or Jefferson production in study area.

formation factor (F) in the numerator of the S_w formula gets very large.

Calculations were made by using the equation $S_w = \sqrt{(F \times R_w)/R_t}$. The value for formation water resistivity (R_w) that proved to best fit the reservoir conditions is 0.03 Ω at formation temperature. The Archie equation for formation factor ($F = 1/\phi^2$) was not used because calculations resulted in unrealistically low hydrocarbon saturation values. Therefore, the modified equation ($F = 0.81/\phi^2$) was used with satisfactory results in calculating S_w. Values for true resistivity (R_t) were taken directly from the deep resistivity logs without much concern about clay effects. Clay affects R_t calculations when water in clays is erroneously considered part of the mobile formation water. Porosity values also were taken directly from density-neutron or density logs in a manner described above. The few wells that had only sonic logs, the acoustic travel time used to determine whether or not sandstone had net porosity was ~66 microseconds/ft. This value was arbitrarily selected because of formation gas effects and the presence of shale and/or interstitial clay. Reservoir characteristics of the Cromwell Sandstone in Scipio NW Field are summarized in Table 4. In this study, a spreadsheet was created incorporating representative values of R_t and cross-plot porosity at a specific depth, which then were used to calculate S_w (Table 3).

and Computed Water Saturation for Wells in Scipio NW Field

Sw=((FxRw)/Rt) When Rw = .030 F=.81/por

Upper Cromwell Sandstone											
Sandstone					max		max	F	F	Sw	Sw
top	subsea	net 8%	gross	Por	ohms	Por	ohms				
nde		nde	nde								
3980	-3103	32	70								
3900	-3010	56	120								
4050	-3138	18	90								
4135	-3398	41	158								
4104	-3344	72	126								
4100	-3400	8	90	4	50	6	20	506	225	55	58
4183	-3446	14	95	8	4			127		97	
4310	-3596	15	84	8.5	5			112		82	
4134	-3421	14	34	13	225			48		8	
4112	-3398	16	42	8	300	7	500	127	165	11	10
4104	-3388	0	26								
4256	-3460	3	17	8	90			127		21	
4240	-3466	0	25								
4012	-3081	84	117	10	12	16	1	81	32	45	97
4212	-3388	16	36	9	13			100		48	
4296	-3441	0	49								
4218	-3485	0	46	3	75			900		60	
4272	-3464	0	47	6	100			225		26	
4167	-3452	28	75	15	50			36		15	
4284	-3565	36	106	15	15	20	20	36	20	27	17
4226	-3351	26	104	11	50	12	2.2	67	56	20	88
4173	-3514	26	57	npl							
4153	-3480	41	72	9	25	10	2	100	81	35	110
4160	-3418	18	48	13	2			48		85	
absent		0	0	13	25			48		24	
4060	-3461	16	41	15	20			36		23	
absent		0	0								
4148	-3481	0	24								
absent?		0	0								
nl		nl	nl								
3940	-3242	53	110	11	2			67		100	
4119	-3300	27	49	11	3			67		82	
3901	-3229	102	133	18	1			25		87	
4272	-3522	24	70								
4398	-3436	35	114	10	2			81		110	
nl		nl	nl								
nl		nl	nl								
3625	-2834	15	62								
3944	-3156	52	71								
3640	-2904	78	106								
absent		0	0								
4036	-3311	0	8	8	5			127		87	
3984	-3290	5	65								

When Rw = .030 F=.81/por Sw=((FxRw)/Rt)

Lower Cromwell Sandstone											
Sandstone					max		max	F	F	Sw	Sw
top	subsea	net 8%	gross	Por	ohms	Por	ohms				
nde											
nde											
4030	-3140	0	16								
4146	-3234	0	61								
absent???											
4248	-3488	0	14								
4192	-3492	0	15								
nde											
4434	-3720	0	5								
4182	-3469	3	10	8	14			127		52	
4172	-3458	0	10								
absent?		0	0								
4302	-3506	0	3								
4286	-3512	3	26	11	9			67		47	
4133	-3202	0	22								
4282	-3458	0	18								
4382	-3527	0	5								
4284	-3557	5	14	8.5	13			112		51	
4358	-3550	0	4								
4265	-3550	2	8	upper Crom							
4428	-3709	0	4	8	12	7	30	127	165	56	41
4362	-3487	0	13								
4268	-3609	0	5			npl					
nde											
4260	-3518	2	10								
4106	-3385	0	2								
4134	-3535	0	4								
4256	-3377	0	2								
4200	-3533	5	22								
4302	-3405	6	19								
nl		nl	nl								
4069	-3371	12	55	13	125			48		11	
4183	-3364	0	8								
4050	-3378	15	38	10	63	15	25	81	39	20	22
4350	-3600	5	15								
4515	-3553	0	7								
nl		nl	nl								
nl		nl	nl								
3702	-2911	0	6								
absent?											
absent		0	0								
3968	-3246	0	12								
4070	-3345	0	2								
4070	-3376	0	6								

When Rw = .030 F=.81/por

Upper Jefferson Sandstone								
Sandstone					max		max	F
top	subsea	net 8%	gross	Por	ohms	Por	ohms	
nde								
nde								
4060	-3170	14	57					
4224	-3312	0	37					
4307	-3570	17	54					
4315	-3555	9	45					
4252	-3552	0	41	6	30			226
nde								
4452	-3738	nde						
4212	-3499	18	38	8	30	10	20	127
4194	-3480	0	nde					
4170	-3454	0	43					
4314	-3518	16	40					
4336	-3562	4	27	8	20			127
4202	-3271	22	36	9	11	11	10	100
4322	-3498	0	32	npl				
4399	-3544	16	40	12	40			56
4318	-3585	22	42	12	15			56
4386	-3578	22	38					
4290	-3575	8	26					
4454	-3735	10	20	8	27			127
4400	-3525	0	11					
4290	-3631	0	26	npl				
nde								
4298	-3556	6	23					
4133	-3412	22	34	8	17			127
4158	-3559	23	35	8	16	12	8	127
4283	-3404	26	40	12	100			56
4242	-3575	2	28	11	43			67
4342	-3445	8	28					
nl								
4142	-3444	6	34					
4222	-3403	0	22+					
4118	-3446	21	44					
4416	-3666	4	18					
4592	-3630	12	33					
nl								
3718	-2927	32	55					
4038	-3250	8	15					
3784	-3048	12	26					
3986	-3264	16	53					
4076	-3351	16	41					
4094	-3400	17	48					

OIL AND GAS PRODUCTION

Cumulative gas production from the upper Cromwell Sandstone in Areas 1 and 2 is estimated to be ~9.2 BCFG from 1971 through February 2002. Most of this comes from Area 1 (8.1 BCF), whereas Area 2 produced only ~1 BCFG. The Jefferson sandstone is productive in eight wells scattered throughout the area, but since production is almost always commingled with other reservoirs, it is difficult or impossible to determine how this reservoir performs individually. However, based upon the thickness and quality of sandstone, the Jefferson reservoirs are generally inferior to those of the Cromwell, and it is likely that combined they produced no more than 0.75 BCFG within the study area. Figure 39 shows the cumlative gas production for each well in the study area. Because the data is incomplete and the zones are commingled, production allocation for individual zones is hard to determine. Many of the wells within this field are still active.

Figure 39 also shows the date of first production, initial production (IP), flowing tubing pressure (FTP), shut-in tubing pressure (SITP), and bottom-hole pressure (BHP) if that information is known. By comparing the date of first production to cumulative production, it is obvious that wells completed early in the field have produced the

TABLE 4. — Reservoir/Engineering Data for Cromwell and Jefferson Sandstone in Scipio NW Field

	Upper Cromwell Sandstone		Jefferson sandstone
	Area 1	Area 2	entire study area
Discovery date	Sept. 1970	April 1966	1975
Reservoir size	~1,780 acres	~900 acres	not determined
Reservoir volume	~19,580 acre-ft	~6,300 acre-ft	not determined
Depth	about 4,100–4,300 ft	about 4,150–4,200 ft	about 4,150–4,300 ft
Spacing (gas)	640 with increased density to 320 acres		
Gas/water contact	multible?, between −3,390 and −3,625	multible?, −3,520, −3,411	not determined
Porosity in non-shaly sandstone (most common)	3–14% (7–8%)	5–14% (6–7%)	5–12% (6–8%)
Permeability	probably 1–30 md	probably 1–30 md	probably less than 1–10 md
Water saturation (S_w) in producing wells (calculated using R_w = 0.03 ohm-m)	about 8–25 %	about 20–35 %	about 13–40 %
Thickness net sand, ≥8% ϕ (about average)	0–28 (11)	20–40 (probably <10 ft saturated)	2–26
Thickness gross sandstone	17–75	50–100	20–40
Reservoir temperature	~120°F	~120°F	~120°F
Gas density	0.62–0.65	0.61	0.58
Z factor (compressibility)[a]	0.86	0.86	0.86
B_g (gas formation volume factor)[b]	~140 std cu ft per reservoir cu ft		
Maximum well-head pressure (PSI)	1,793	1,850	not known
Initial reservoir press (PSI)	~1,980	est. 1,980	not known
Initial pressure gradient	0.47 PSI/ft	0.47 PSI/ft	probably same as Cromwell
OGIP[c] (volumetric-field)	8,200 MMCF	1,800 MMCF	not determined
Cumulative field gas (through Feb. 2002)	8,133 MMCF	1,085 MMCF	±750 MMCF?
Percent gas recovery to date	99%	60%	not determined
Recovery MCF/ac-ft (field to date)	~415 MCF/ac-ft	~172 MCF/ac-ft?	not determined

[a]Compressibility factor (Z) estimated from standard reservoir engineering chart using T_{res} and P_{res} values listed in this table. T_{res} is in °Rankine (add 460° to reservoir temperature that is measured in °F), P_{res} = reservoir pressure.

[b]B_g calculated using the formula: $B_g = \frac{35.4 \times P_{res}}{T_{res} \times Z}$. The Z factor is stated above.

[c]Original gas in-place (OGIP) determined from the following formula: Reserves (MCF) = 43.56 × Area (acres) × Sand thickness (ft) × Porosity (%) × (1-S_w) × B_g.

most gas, because they have been on line longer and they encountered nearly virgin reservoir pressure. There is good pressure communication in most Cromwell reservoirs, so recently drilled wells always find depleted reservoirs. No liquids were reported produced in this field from the Cromwell or Jefferson.

On the basis of volumetric calculations, wells in the upper Cromwell Sandstone in Area 1 have produced almost 99% of the original recoverable gas in place, which is estimated to have been 8.2 BCF (Table 4). This apparently high recovery is misleading because the reservoir volume was calculated using an 8% net sandstone cutoff. The reservoir volume is probably larger inasmuch as gas is produced from sandstone having porosity as low as 6%. The lower value would increase the reservoir volume, thereby decreasing the recovery factor. All the wells have reached a depleted flowing pressure of only a few hundred PSI. There is considerable room for error in these reserve calculations because of such imprecise factors as reservoir thickness and especially S_w. The ultimate recovery from the upper Cromwell in Area 1 is estimated to be about 415 MCF per acre foot. In Area 2 it is probably only 172 MCF per acre foot, but this figure is based on very inadequate reservoir information.

Most Jefferson production is commingled, so its actual volume is unknown. One well in the SE¼NW¼ sec. 16, T. 8 N., R. 13 E., produces entirely from the Jefferson, and it has produced only 171 MMCFG since completion in 1977. That well encountered a better-than-average Jefferson sandstone section, so it is likely that most other Jefferson wells produced even less. Another well, in NE¼ sec. 8, T. 8 N., R. 13 E., produced ~910 MMCFG from four different commingled reservoirs. The Jefferson seems to be the best reservoir in that well and probably contributed much of the total cumulative production. As previously noted, the Jefferson sandstone has porosity similar to that in the Cromwell, but resistivity separation on logs is very low, indicating low permeability. Overall, the Jefferson is a poorly performing reservoir.

The better wells in Scipio NW Field all produce from the upper Cromwell Sandstone and are located in structurally high positions within their respective fault blocks. They all had virgin or nearly virgin pressure (about 1,400–2,000 PSI) and above average net sandstone thickness. The highest volume well produced >3 BCF, followed by wells having estimated cumulative production of 2.5 BCF, 1 BCF, 0.9 BCF, 0.8 BCF, and 0.6 BCF each. Recently completed wells produced only small amounts of gas.

Initial production rates for the better upper Cromwell wells were between 1 and 2 MMCFGPD. Many wells reported initial production of 600–700 MCFGPD, but these rates diminished rapidly. The initial shut-in tubing pressure (SITP) of the discovery well in Area 1 (SW¼ sec. 4, T. 8 N., R. 13 E.) was almost 1,800 PSI but dropped 400–500 PSI in nearby wells in less than a year. Currently, SITP is only a few hundred PSI throughout the field. Flowing tubing pressure (FTP), when compared to SITP, is another indication of reservoir quality. The closer the two pressures are to each other, the better the reservoir performance is. The FTP in the discovery well of Area 1 was 1,250 PSI, so the ratio of FTP/SITP was 0.7—an extremely good value. This ratio cannot be determined for every well because pressure data is incomplete. Two other wells, which did have both pressure values, had ratios of ~0.5. The one well that produced solely from the Jefferson had a ratio of <0.4. The flowing pressure from very tight rocks is usually small in relation to the shut-in pressure.

PRODUCTION-DECLINE CURVES (Figures 40, 41, and Table 5)

Production-decline curves for four wells in Scipio NW Field that have good pressure and production histories are shown in Figure 40. All data used to construct these

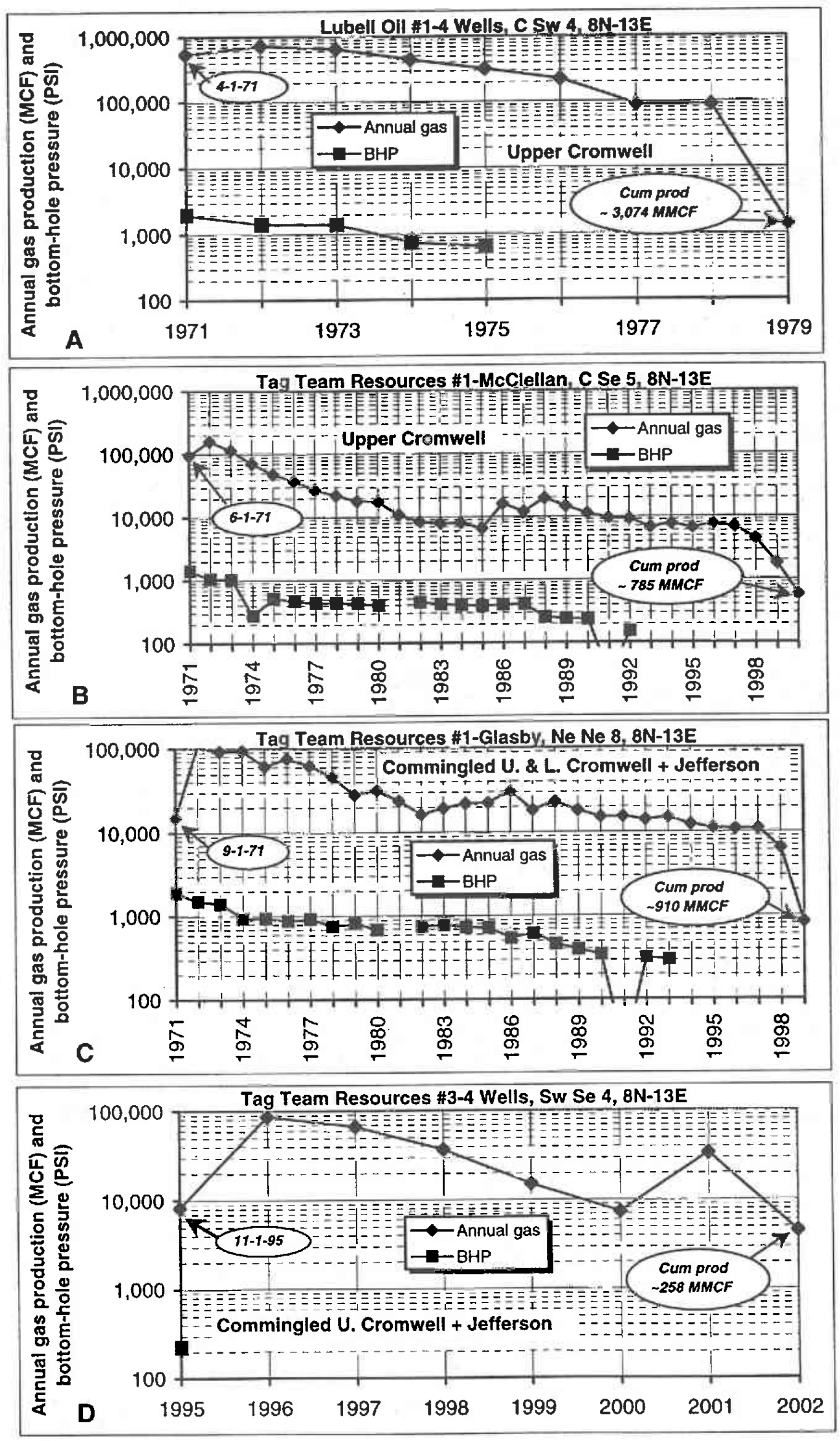


Figure 40. Production- and pressure-decline curves for four wells producing from the Cromwell Sandstone in Scipio NW Field through June 2002.

TABLE 5. — Annual Production and Pressure Data Attributable Primarily to One Zone for Four Wells in Scipio NW Field

	Upper Cromwell *First production 4-71* Lubell Oil Company 1-4 Wells C Sw 4, 8N-13E			Upper Cromwell *First production 6-71* Tag Team Resources 1 McClellan C Se 5, 8N-13E			U+L Cromwell & Jefferson *First production 9-71* Tag Team Resources 1 Glasby Ne Ne 8, 8N-13E			U Cromwell & Jefferson *First production 11-95* Tag Team Resources 3-4 Wells Sw Se 4, 8N-13E		
Date	Annual Gas MCF)	Cum prod (MCF)	Bottom-hole Pressure	Annual Gas MCF)	Cum prod (MCF)	Bottom-hole Pressure	Annual Gas MCF)	Cum prod (MCF)	Bottom-hole Pressure	Annual Gas MCF)	Cum prod (MCF)	Bottom-hole Pressure
1971	540,066	540,066	1,990	95,077	95,077	1,406	15,123	15,123	1,912			
1972	729,497	1,269,563	1,439	159,109	254,186	1,045	101,928	117,051	1,524			
1973	647,830	1,917,393	1,418	113,631	367,817	1,031	92,299	209,350	1,423			
1974	441,670	2,359,063	737	70,578	438,395	275	93,688	303,038	940			
1975	315,520	2,674,583	638	48,201	486,596	508	60,701	363,739	940			
1976	219,222	2,893,805		37,332	523,928	474	75,300	439,039	873			
1977	89,930	2,983,735		27,115	551,043	441	61,334	500,373	918			
1978	89,008	3,072,743		22,005	573,048	441	46,354	546,727	762			
1979	1,401	3,074,144		17,980	591,028	433	28,205	574,932	812			
1980				17,921	608,949	400	31,496	606,428	684			
1981				10,860	619,809		23,401	629,829				
1982				8,326	628,135	441	16,383	646,212	750			
1983				7,810	635,945	408	19,118	665,330	784			
1984				7,957	643,902	397	21,637	686,967	728			
1985				6,530	650,432	381	22,139	709,106	713			
1986				16,004	666,436	396	30,428	739,534	541			
1987				11,950	678,386	404	18,096	757,630	627			
1988				19,533	697,919	250	23,048	780,678	462			
1989				14,471	712,390	240	18,052	798,730	396			
1990				11,270	723,660	231	15,036	813,766	342			
1991				9,408	733,068	30	15,101	828,867	22			
1992				9,167	742,235	150	13,910	842,777	318			
1993				6,688	748,923		14,807	857,584	302			
1994				7,613	756,536		12,205	869,789				
1995				6,553	763,089		11,133	880,922		8,162	8,162	225
1996				7,605	770,694		10,772	891,694		86,219	94,381	
1997				7,047	777,741		10,906	902,600		66,650	161,031	
1998				4,493	782,234		6,372	908,972		36,697	197,728	
1999				1,777	784,011		832	909,804		15,014	212,742	
2000				586	784,597					7,317	220,059	
2001										33,471	253,530	
2002										4,466	257,996	
Cumulative Production	**3,074,144 MCF**			**784,597 MCF**			**909,804 MCF**			**257,996 MCF**		

Data from IHS Energy, current through June 2002.

graphs is included in Table 5. Two wells have produced solely from the upper Cromwell and demonstrate the effects of reservoir thickness, quality, and depletion over time (Plots A, B). The other two wells (Plots C, D) produced from commingled reservoirs.

The upper plot (A) shows the production curve for the Lubell No. 1-4 Wells well located in the C SW¼ sec. 4, T. 8 N., R. 13 E. This is the field discovery well of Area 1, and its cumulative production is ~3 BCFG since September 1970. In that well, the upper Cromwell has 16 ft of net sandstone having estimated 10–12% porosity (no porosity log is available). The reservoir thins significantly 0.5 mi west where the Tag Team No. 1 McClellan well has only 3 ft of net sandstone (plot B). That offset well was brought on line only 2 months after the Lubell well, but the bottom-hole pressure was 530 PSI lower. The McClellan well produced only 785 MMCFG compared to the ~3 BCFG produced in the Lubell well. The Tag Team No. 1 Glasby well (plot C), directly south of the wells graphed in plots A and B, came on production 5 months after the Lubell No. 1-4. The upper and lower Cromwell in the Glasby well has no porosity >6%, whereas the Jefferson zone has unusually good porosity of 8–10% in 16 net ft of sandstone. The Glasby well was completed in the upper and lower Cromwell, the overlying Union Valley Limestone, and the underlying Jefferson sandstone. It had a virgin bottom-hole pressure of 1,912 PSI (probably in the Jefferson) and has made 910 MMCF—a substantial amount of gas. The upper Cromwell is the subordinate reservoir in the Glasby well, and more than half the cumulative production is probably attributable to the Jefferson zone. The last plot in Figure 40 (D) illustrates the production history of the Tag Team No. 3-4 Wells well located about 0.25 mi southeast of the discovery well (plot A). It encountered 14 ft of net sandstone in the upper Cromwell and 18 ft of net sandstone in the Jefferson zone. Both zones have unusually large crossover of 12–15 porosity units on the density and neutron logs. This usually indicates pressure depletion—a condition verified by an initial bottom-hole pressure of only 225 PSI. Although commingled, the well has produced only ~258 MMCFG since completion in November 1995.

The ultimate production of wells plotted in Figure 40 is primarily a function of the completion date, reservoir quality, thickness, commingling, and pressure communication from nearby wells. Three of the wells were drilled within 5 months of each other in 1971. The well represented by plot D was drilled in 1995. The discovery well, plot A, produced entirely from the upper Cromwell and the decline is relatively uniform and gradual over most of its 9-year history. Production from the well shown in plot B declined much more rapidly because the upper Cromwell is tighter and was partially pressure-depleted by the Lubell well of plot A. What caused the temporary reversal of decline in 1986 is unknown. The decline curve for the Glasby well, plot C is typical of many Jefferson gas wells. Production and pressure both declined rapidly in the early years, followed by 15 years of modest decline. The well represented by plot D illustrates severe depletion of two commingled reservoirs.

Pressure/production plots for the three wells having good data are shown in Figure 41. They show convergence toward an initial bottom-hole pressure of ~2,000 PSI, which indicates they all had nearly the same initial reservoir pressure. The shapes of the curves differ, however, from well to well. The upper curve represents production from the Lubell well in C SW¼ sec. 4, T. 8 N., R. 13 E., which has produced >3 BCFG from the upper Cromwell. Considerably more gas was produced per PSI drawdown in that well than in any of the other wells. The bottom curve represents production from the McClellan well in SE¼ sec. 5, T. 8 N., R. 13 E., which also produced only from the upper Cromwell. The steep decline indicates that that well will not produce much more than its current total of 785 MMCFG, because the reservoir is tight and that much of the gas was siphoned away by the Lubell well. The middle curve represents the commingled production from the Glasby well. Most of that gas came from the Jefferson zone, and it is a poor reservoir compared to the upper Cromwell.

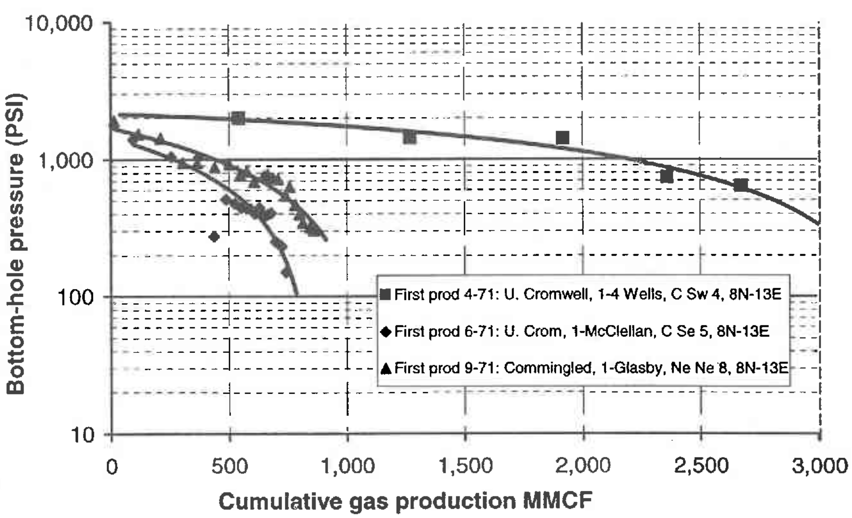


Figure 41. Graph showing relationship between pressure and cumulative gas production for three wells in Scipio NW Field having good pressure data from the Upper Cromwell Sandstone.

DRILLING AND COMPLETION PRACTICES

Wells in Scipio NW Field vary in depth from 4,000 to a little more than 5,000 ft. In order to fully penetrate the Jefferson sandstone, they must be drilled to at least 4,500 ft and are drilled using traditional water-based drilling fluids. Operators set 8⅝-in. surface casing to between 250 and 400 ft, then set either 4½- or 5½-in. production casing to TD. Completion reports show that many wells were acidized with 500–2,000 gallons of 7.5% HCl. In all the productive wells, the Cromwell interval was stimulated with a fracture treatment. In the 1970s this consisted of various treated gels (commonly water gel). Amounts range from 5,000 to 25,000 gallons of gel plus 25,000–35,000 pounds of sand. More recently, nitrogen foam has been used to reduce formation damage due to water sensitive clays. Foam treatments utilize 600,000–900,000 standard cubic ft of nitrogen foam plus 40,000 pounds of sand. Dry-hole costs are estimated to be $84,000 for a conventional vertical well drilled to a depth of 4,500 ft. The cost of a well completed in a single zone including drilling, completion, and stimulation is about $179,000. These are estimates typical for small operators who usually contract with more competitive service companies. The wells usually take 2–5 weeks to drill.

PART III

Raiford SE Field

Cromwell and Jefferson sandstone gas reservoirs in T. 9 N., Rs. 14–15 E., south-central McIntosh County, Oklahoma

INTRODUCTION

The Raiford SE Field is located in south-central McIntosh County, southeastern Oklahoma (Fig. 42). The 54-section study area is in the center of T. 9 N., Rs. 14–15 E., and is ~12 mi northeast of Scipio NW Field (Part II of this report). Raiford SE is located near the center of the Cromwell play in the central part of the Arkoma Basin as identified in Plate 1. The study area includes three closely spaced but separate gas pools that produce mainly from the upper Jefferson sandstone, Cromwell Sandstone, and Hunton limestone. These pools produce along upthrown fault blocks and encompass only a part of the Raiford SE Field as established by the Oklahoma Stratigraphic Nomenclature Committee of the Mid-Continent Oil and Gas Association. This happens because other reservoirs pro-

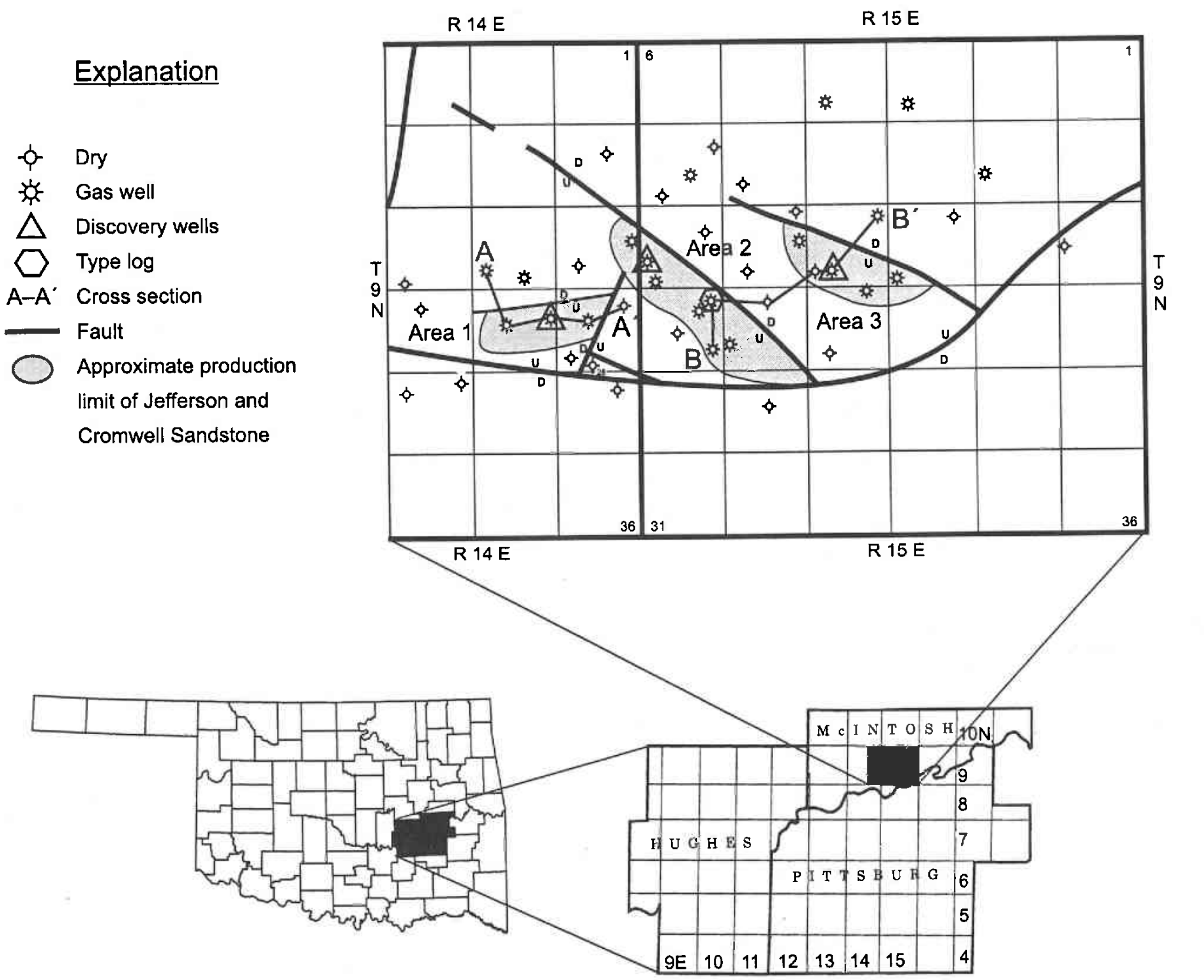


Figure 42. Generalized location map of Raiford SE Field, south-central McIntosh County, Oklahoma. Lines of cross sections A–A′ (Fig. 46) and B–B′ (Fig. 47) are shown.

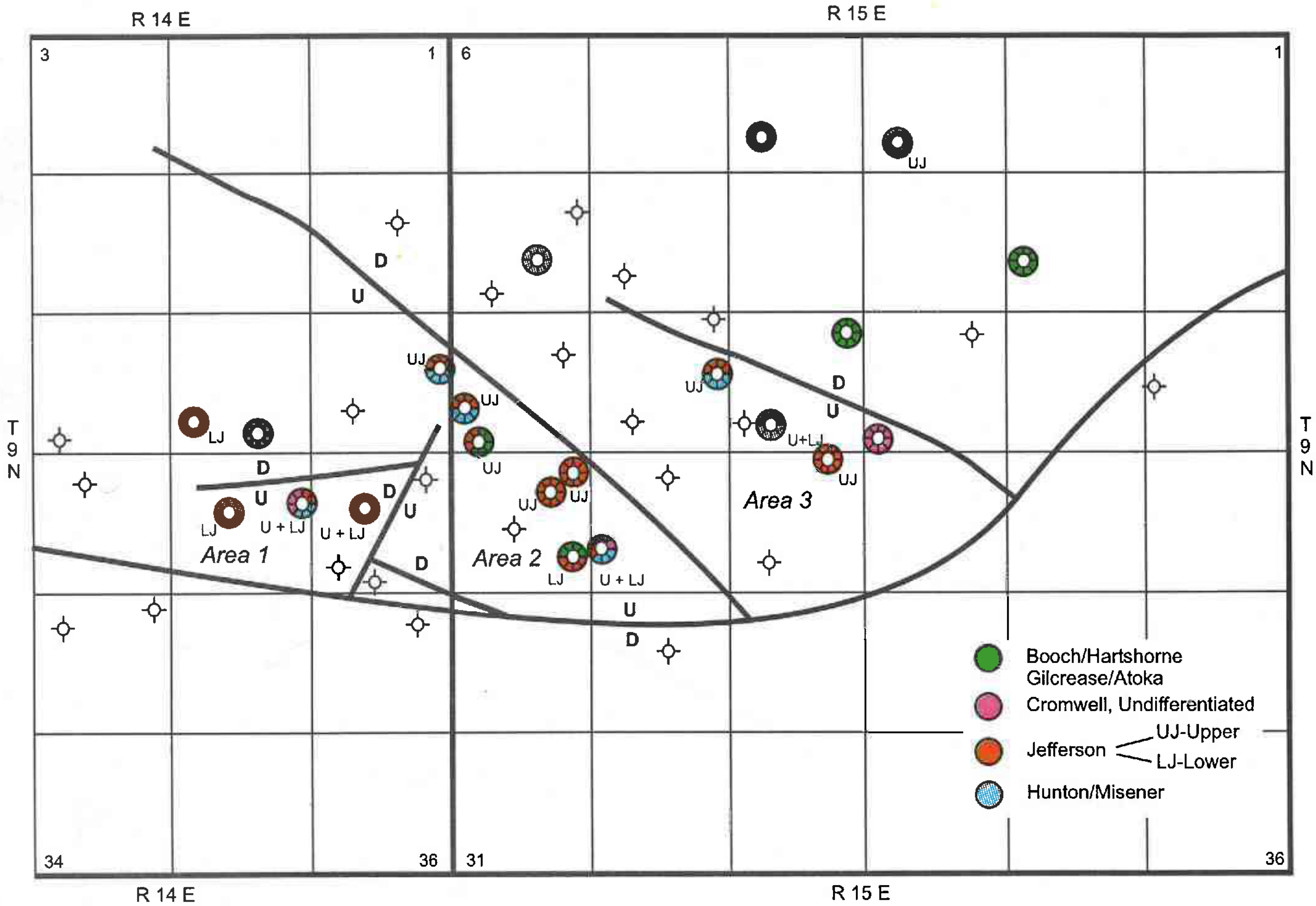


Figure 43. Production code map showing producing reservoirs in Raiford SE Field, south-central McIntosh County, Oklahoma.

duce elsewhere in the field including the younger Atokan Gilcrease sandstone. The locations of wells producing from the Cromwell and Jefferson reservoirs are shown in Figure 43, but only wells that penetrate them are included on maps in this study.

The stratigraphic units in this study are believed to be correlated correctly, but the nomenclature for some units is not agreed upon by all geologists. Consequently, what is identified in this report as upper Jefferson may be called lower Cromwell by others. Production limits of the individual gas pools are defined on the basis of well logs; there was no seismic information available to the author. Dry holes in the Cromwell or Jefferson occur because the reservoir is structurally low and wet, or in some wells the sandstone is tight or pressure depleted—a condition that can usually be identified on porosity and resistivity logs.

Producing pools within Raiford SE Field generally are located where they are structurally high along upthrown fault blocks. The spatial distribution of gas wells producing from the upper Jefferson conforms to the net sandstone isopach map of that reservoir. However, the location of Cromwell producers appears unrelated to its net isopach map. Therefore, mapping sandstone strictly for the purpose of predicting stratigraphic traps is not always useful in this area. Nevertheless, it is always important to know the distribution pattern of these reservoirs to assist development and exploration drilling.

As of February 2002, there were a total of 14 wells producing from the Cromwell and Jefferson: three in Area 1, seven in Area 2, and four in Area 3. Outside of these areas there are two additional wells that produce from either the Jefferson or the Cromwell and several wells that produce from younger reservoirs. Multiple zone completions are common, making determination of individual zone performance difficult.

The thickness of Cromwell Sandstone in Raiford SE is unaffected by faulting and is not eroded on upthrown fault blocks as it appears to be in Scipio NW Field. The sandstone is distributed in north–south-trending bars that reach a thickness of >120 ft in the southern half of the study area but are <70 ft thick in the north. This seems to be related to regional deposition trends rather than structure. Significant net Cromwell Sandstone with porosity >7% is generally present only in the very center of the study area where it reaches a maximum thickness of 86 ft.

The upper Jefferson (lower Cromwell?) sandstone occurs more or less as a blanket deposit rather than as a discrete bar. The gross sandstone gradually thickens to 60 ft in the south from 25 ft in the northern part of the study area. However, the amount of porous sandstone is generally much thinner. Gas wells producing from this reservoir have a direct relationship to the thickness of net

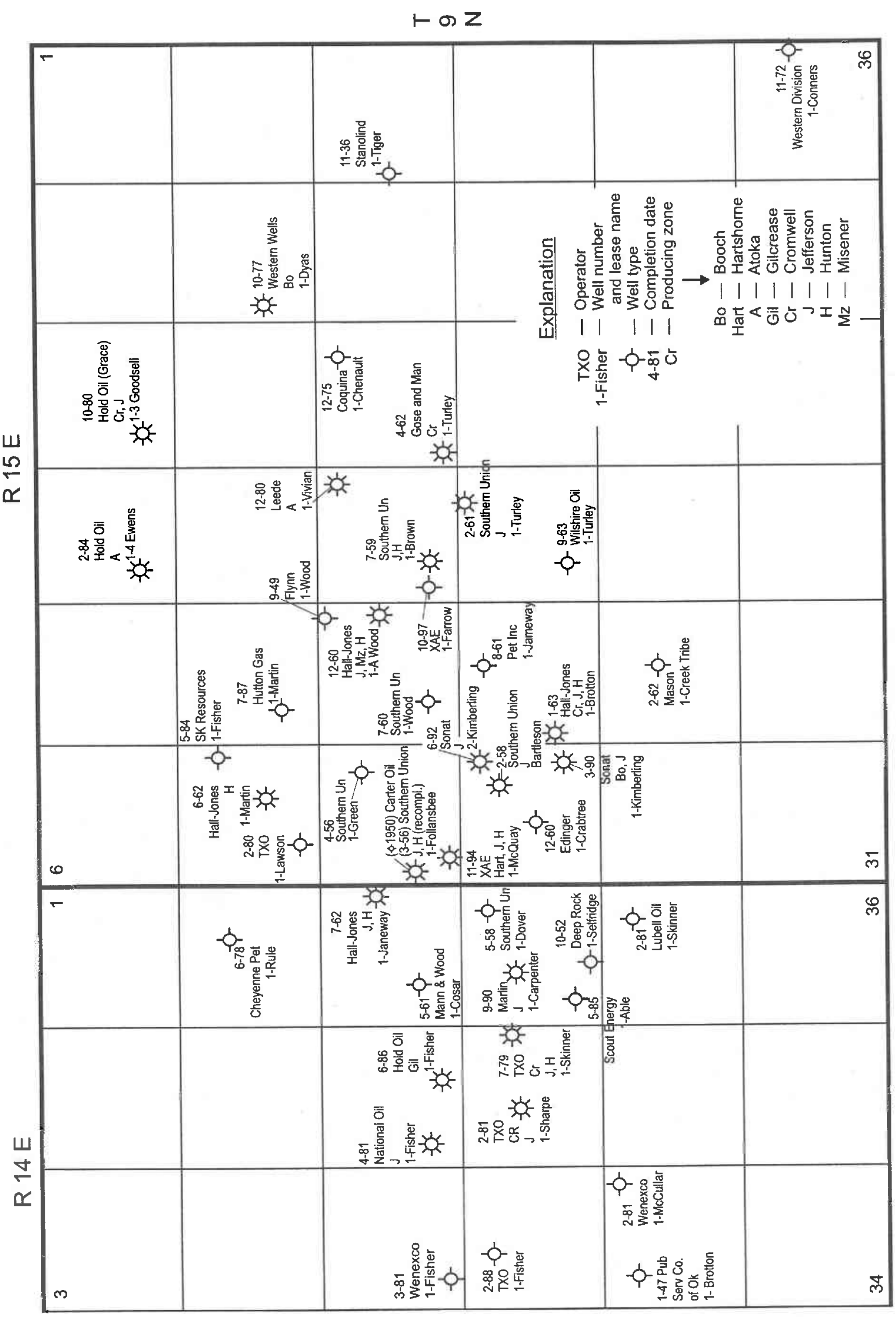


Figure 44. Well information map showing operators, well numbers, lease names, producing reservoirs, and completion dates in Raiford SE Field, south-central McIntosh County, Oklahoma.

sandstone which is generally 15–25 ft thick, with a maximum thickness of 30 ft.

The lower Jefferson sandstone is much thinner and occurs in discrete north–south-trending bars 5–25 ft thick. In a manner consistent with regional trends, the amount of lower Jefferson sandstone in the study area diminishes northward and thickens to the south. When using a 7% porosity cut-off, the net sandstone is often too thin to serve as a significant reservoir, but locally the net sandstone thickens to 6–10 ft and is productive.

Sandstone within individual bars tends to be continuous and permits good pressure communication. This is particularly true of the Cromwell and upper Jefferson reservoirs of this study. Even so, pressure depletion is compartmentalized from bar to bar and structure to structure. Reservoir depths vary from 4,200 to 4,500 ft. Judging from cores in other wells to the west, the Cromwell Sandstone probably consists chiefly of quartz grains with highly variable carbonate cement.

Well logs of discrete sandstone zones in the Cromwell and Jefferson intervals depict highly variable textural profiles. A definitive coarsening-upward textural pattern characterizes the Jefferson sandstone which is typical of marine deposits. But log shapes of individual Cromwell Sandstone zones are not so clear. In particular, an obvious gradational lower contact takes place less frequently and is not always obvious on well logs. In many instances, a rapid transition from shale to sandstone occurs causing the log shape to appear blocky. Therefore, interpreting the depositional origin of Cromwell sequences solely from the response of well logs can be misleading. When used in conjunction with core data and regional trend analysis, however, the subtle textural variations implied from well logs is very suggestive of rapid marine deposition. Textural profiles are best demonstrated by the gamma-ray and resistivity logs included in the field cross sections (A–A´ and B–B´). They also may be inferred from SP logs noting that such interpretations can be ambiguous and inaccurate.

HISTORY OF DEVELOPMENT IN RAIFORD SE FIELD

Stanolind Oil Company drilled the first Cromwell penetration in this study area in 1936. It was in sec. 13, T. 9 N., R. 15 E., tested dry, and has no well log available. Subsequent wells drilled during the 1940s, ’50s, and ’60s were responsible for discovering the Cromwell and Jefferson gas pools. The largest of these pools, Area 2, has produced over 7.3 BCFG, mostly from the upper Jefferson sandstone. This pool (see Fig. 42) was discovered in 1956 by Southern Union when they recompleted the 1-Follansbee well that was originally drilled and abandoned by Carter Oil in 1950. The Follansbee well is located in the NW¼SW¼ sec. 18, T. 9 N., R. 15 E., and produced about 2.3 BCFG from 18 net ft of upper Jefferson sandstone. Two years later, Southern Union drilled another well ~1 mi to the southeast in sec. 19. That well had 20 net ft of upper Jefferson sandstone and produced almost 3.4 BCFG. Neither of the Southern Union wells were produced until a pipeline connection was available in 1961. Two other wells were drilled in 1962–63, and three additional wells were drilled in 1990, 1992, and 1994, respectively. The wells drilled during the 1990s found depleted reservoirs and produced only small amounts of additional gas.

Area 3 (Fig. 42) was discovered in 1959 by the Southern Union #1 Brown well and produces from the upper and lower Jefferson, Cromwell, and Hunton. The upper Jefferson and Cromwell produced >2.1 BCFG, and the Hunton produced an additional 883 MMCFG. The Brown well was quickly offset by two additional wells in 1960 and 1961, and they all went on line later in 1961–62 after completion of local gathering systems. The Brown well offsets to the south a dry hole drilled by Flynn Oil in 1949.

The smallest of the three producing areas, Area 1 (Fig. 42) was discovered by the TXO #1 Skinner well in 1979. This area produces from the Cromwell, upper and lower Jefferson, and possibly the Hunton. Cumulative production from all reservoirs is 876 MMCFG, which probably is divided equally between the Cromwell and Jefferson. The Skinner well was offset half a mile to the west one year later and half a mile to the east in 1991. The discovery well produced 515 MMCFG, but the offsets were pressure depleted and produced only 169 and 192 MMCFG, respectively.

Figure 44 is a well information map that identifies operators, well number and lease, and completion date of all wells in the study area that penetrate the Cromwell.

STRATIGRAPHY

The stratigraphy of the Cromwell/Jefferson intervals and bounding strata within Raiford SE Field is depicted on a Type Log in Figure 45. In a normal succession, the Cromwell Sandstone (colored red in field cross sections) overlies the Jefferson sandstone (colored yellow). As simple as this may seem, a nomenclature problem exists for the principle sandstone reservoir of this field alternatively identified as either the upper Jefferson or lower Cromwell sandstone. The correct determination depends on accurately identifying the Springer shale which separates the Cromwell from the underlying Jefferson. This shale is usually only 10–30 ft thick and has anomalously low resistivity (high conductivity). Unfortunately, a shale interval with similar characteristics exists between the upper and lower Jefferson sandstone intervals, complicating the interpretation (see conductivity log of Fig. 45). In reference to regional cross sections and correlations within this field, the principle reservoir of controversy is herein identified as the upper Jefferson.

The Cromwell on the type log (Fig. 45) and in field cross sections (Figs. 46, 47, in envelope) consists of an upper and lower unit, but whether or not these accurately portray sub-members is not certain. The division is made arbitrarily at the most consistent shale split in the upper part of the sandstone interval. When both units are combined, the Cromwell has a maximum gross thickness of ~120 ft sandstone. These units commonly occur in thick, massive, uninterrupted bodies of sandstone that are continuous for a mile or more. Beyond Raiford SE Field the massive sandstones may split into one or more zones separated by shale, or they may become so calcareous as to be nearly indistinguishable from limestone. In the

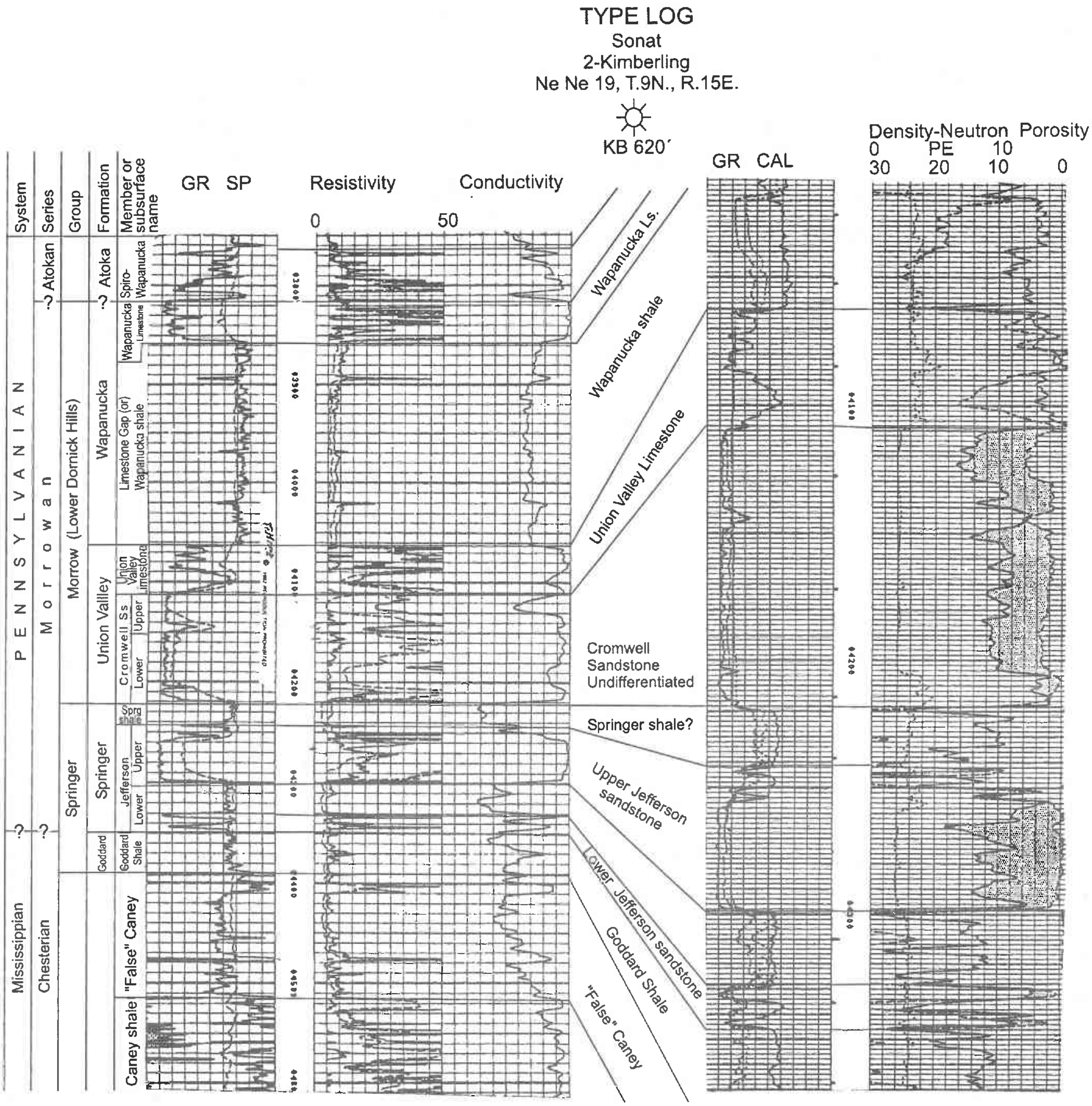


Figure 45. Type log for Raiford SE Field showing formal and informal subsurface nomenclature of the Morrowan Series as used in the Arkoma Basin of southeastern Oklahoma. GR = gamma ray; SP = spontaneous potential; CAL = caliper; PE = photo electric.

Raiford SE area the gross thicknesses of the Cromwell and upper Jefferson intervals do not change abruptly, either by facies changes or erosion on upthrown fault blocks.

The underlying Jefferson interval is informally divided into upper and lower sandstone zones that are separated by shale. This shale has characteristics similar to the Springer shale, making the distinction difficult in some areas. The upper Jefferson contains up to 50 ft of sandstone, which is as thick as any Jefferson sandstone in the Arkoma Basin, whereas the lower Jefferson is much thinner and seldom contains >20 ft of sandstone. The Goddard Shale underlies the Jefferson interval and also is characterized by low resistivity. It is not as thick in the Arkoma Basin as it is in the Anadarko Basin and is distinguished by a smooth, high gamma-ray response typical of deep-water marine shale.

The Union Valley Limestone Member overlies the Cromwell Sandstone. In the western half of the study area the relationship between these two members is easy to distinguish, because they are separated by shale as shown in the type log (Fig. 45). Farther east, however, the Union Valley Limestone splits into two parts with shale in between. Where this happens, the lower limestone bed rests directly on top of the Cromwell Sandstone, making distinction of their boundaries more difficult to determine. In this situation, the contact is most easily picked by using a density-neutron log suite, because the Cromwell Sandstone has relatively high porosity compared to the tight Union Valley Limestone. If a PE log is available, this measurement is even more diagnostic, since quartz sandstone has values in the range of 2–3, whereas limestone has values of 3–5. Differentiating the contact becomes even more confusing when it is gradational; the Cromwell Sandstone becomes limy at its top, or the Union Valley Limestone becomes sandy at its base. Resistivity, SP, and gamma-ray logs alone do not always adequately define this contact but are useful in conjunction with other logging tools. Problematic picks of the Cromwell top also are seen on some well logs in the regional and field cross sections.

The Wapanucka Formation directly overlies the Union Valley Limestone. Most of it consists of shale informally called the Wapanucka shale or Limestone Gap shale. The very upper part of the formation includes a widespread limestone called the Wapanucka Limestone. Because of its regional extent, it was used as the datum in the structure map (Pl. 3). The Wapanucka Limestone contains two limestone sequences that are distinct in this area. The lower sequence contains mostly limestone, whereas the upper has increasing amounts of shale and grades upward into the Spiro sandstone. A distinctive thin shale break separates the two Wapanucka limestone sequences and defines the top of the Wapanucka Limestone as used in this study. The overlying limestone, shale, and sandstone sequence is referred to simply as Spiro/Wap on the cross sections.

CROSS SECTIONS

The stratigraphy and structural details of the Cromwell Sandstone and Jefferson sandstone are best shown by two detailed cross sections across Raiford SE Field. The selection of wells used in both sections was dictated by log quality, depth, and availability of gamma-ray and porosity logs. The upper part of each cross section is structurally controlled and the lower part is a detailed stratigraphic reconstruction. Cross section A–A′ (Fig. 46) is oriented west to east and shows the Cromwell and Jefferson stratigraphy, a gas/water contact, and the position of two faults bounding producing Area 1. Cross section B–B′ (Fig. 47) shows fault relationships, stratigraphy of the Cromwell and Jefferson reservoirs, and the nature of gas/water contacts in Areas 2 and 3. Both stratigraphic cross sections use the base of the conductive Springer shale for the datum. The datum for both structural sections is mean sea level.

Cross Section A-A′ (Figure 46)

This west-to-east cross section best illustrates log characteristics of the Jefferson and Cromwell reservoirs where they are productive and the nature of fault displacements north and east of producing Area 1. The Wenexco 1-Fisher well at location 1 is on the downthrown, north side of a local east–west fault. At this location the Cromwell contains three relatively thin, low-porosity sandstone zones that are non-productive, whereas the lower Jefferson contains one thin zone that is completed. The Jefferson reservoir pinches out downdip to the north and is fault bound on the south, making a perfect combination trap. The upper part of the Cromwell north of the fault is adjacent to the lower part of the Cromwell south of the fault. Similarly, the upper Jefferson is faulted against Jefferson shale and the lower Jefferson is faulted against Goddard Shale. From this interpretation, it is apparent that most porous zones in either the Cromwell or Jefferson are not interconnected across the fault. Additionally, there seems to be no pressure or fluid communication across the fault in regards to the juxtapositioning of reservoirs, indicating that the fault trace is sealed. Hydrocarbons in the Wenexco well would tend to move updip, to the south toward the fault.

About 1,200 ft south of location 1, a small fault having about 40–50 ft of displacement is crossed, which is the north-bounding fault for Area 1. South of this fault in the TXO 1-Sharp well at location 2, both the Cromwell and Jefferson reservoirs produce. Three zones in the upper and lower parts of the Cromwell are perforated where porosity ranges from 5% to 8% and resistivity is close to or >50 Ω. The upper Jefferson, though well developed, is wet as noted by the low resistivity of <5 Ω. Both zones in the lower Jefferson interval also are perforated since porosity is >7% and resistivity is greater than 30–35 Ω.

Only 2,800 ft to the east, the TXO 1-Skinner well at location 3 is slightly higher and the upper Jefferson is productive, whereas it is wet at location 2. The gas/water contact is identified on the resistivity log where it decreases from 40 Ω to <5 Ω. In the Skinner well, both zones in the Cromwell are perforated and produce where the logs show good SP deflections, high resistivity, and porosity ≥7%. The lower Jefferson has similar log characteristics and is productive. The TXO well at location 3 is the pool discovery well in producing Area 1.

The Marlin well at location 4 is about half a mile east of location 3 and is the highest well in producing Area 1. Most of the Cromwell in this well is tight and has no gas potential. The most porous zone (at ~4,327 ft) calculates wet with resistivity of only ~20 Ω. The upper Jefferson produces above a distinct gas/water contact where the resistivity drops to 5 Ω. The lower Jefferson is perforated but appears to be relatively tight as indicated by a weak SP response and low cross-plot porosity on the density and neutron logs. The Marlin well was drilled 10 years after the Skinner well at location 3, but because of pressure depletion and tight reservoirs it produced only 0.2 BCFG. A down-to-the-west fault separates the wells at locations 4 and 5. The Southern Union 1-Dover well at location 5 is on the upthrown side of the fault but is structurally lower than producing wells located farther to the northeast. The Cromwell and upper Jefferson reservoirs are either wet or tight in the Dover well.

Cross Section B–B′ (Figure 47)

This section crosses producing Areas 2 and 3 in a southwest to northeast direction. It is intended to show log characteristics and structural relationships of the Cromwell and Jefferson reservoirs in the central and eastern parts of Raiford SE Field. In this area, the upper Jefferson sandstone is the only productive reservoir in cross section B–B′. The Cromwell Sandstone is either wet or tight.

In the TXO well of location 1, Area 2, the Cromwell and upper Jefferson reservoirs are either wet where porosity develops (note resistivity less than 10–15 Ω) or tight (ϕ <6%). The lower Jefferson with porosity ~10% is the only sandstone perforated. The gas accumulation in the lower Jefferson is trapped stratigraphically since the same zone becomes tight updip before being truncated by the bounding fault. Location 1 is structurally low in producing Area 2 and is downdip water leg of both the Cromwell and upper Jefferson.

At location 2, ~0.6 mi north, the Sonat well is structurally high in Area 2, yet only the upper Jefferson is productive. In the thick Cromwell interval where porosity varies from 6% to 11% (between 4,110–4,130 ft and 4,183–4,204 ft), resistivity falls below 5–15 Ω, indicating a wet reservoir. However, the underlying upper Jefferson sandstone (Lower Cromwell?) is productive throughout the entire sandstone interval and has porosity of 6–9% and resistivity mostly >100 Ω. The large separation between the density and neutron curves indicates pressure depletion—a fact supported by the very low reservoir pressure. The Sonat well was drilled in 1992 and is a close offset to a well drilled in 1958 that has produced 3.4 BCFG.

A fault separates the Sonat well at location 2 from the Petroleum Inc. well at location 3. It has displacement of ~130 ft, up to the south, and is the trap for upper Jefferson gas production in Area 2. North of the fault in the Petroleum Inc. well, all zones having good porosity in the Cromwell and Jefferson are wet since the corresponding resistivity is <25 Ω. Location 3 represents the structurally lowest part of producing Area 3.

About two-thirds of a mile northeast of location 3, XAE-Farrow well encountered thick Cromwell and Jefferson sandstone intervals but was abandoned as a dry hole. In that well, the Cromwell Sandstone was mostly tight except near the base. In this lower zone, porosity increased to 6–8%, but resistivity was <25 Ω, an indication that it is wet. The upper Jefferson has excellent porosity upwards to 10%, but the sandstone interval appears depleted overall (note large density-neutron separation), and the bottom half appears to have higher water saturation where the resistivity drops from >35 Ω to <10 Ω. This change in formation resistivity may indicate a gas/water contact in the upper Jefferson as noted on the cross section. The XAE well was drilled in 1997 as a west offset to the Southern Union 1-Brown well (location 5). The latter well was completed in the same Jefferson zone 38 years earlier.

The Southern Union well at location 5 is the discovery well in producing Area 3 and is structurally high to the XAE well at location 4. Even so, the Cromwell Sandstone is not productive because it appears to be mostly tight. This is difficult to determine because the interval was logged using a sonic tool, which is more ambiguous than modern density-neutron cross-plot measurements. Generally speaking, sonic logs can lead to erroneous porosity values when the reservoir has interstitial clay or shale laminations, or has fractured gas. All of these conditions may be present in the Cromwell. The underlying upper Jefferson sandstone is a much better reservoir and is entirely gas saturated. This is noted on the well logs by a large SP response, high resistivity, and relatively longer travel times (indicating higher porosity) on the sonic log.

A fault separates the Southern Union well from the Leede well at location 6. It has <150 ft of displacement, up to the south. The Leede well at location 6 has a somewhat thinner Cromwell Sandstone interval on the downthrown side of the fault. Both the Cromwell and Jefferson sandstones at this location appear to be tight or wet and are nonproductive. Neither fault crossed by cross section B–B′ traps gas in the potential Cromwell zones.

STRUCTURE (Figure 48)

Raiford SE Field is in the central part of the Arkoma Basin where structural deformation is relatively minor. Nevertheless, minor faults exist in this study area and are the principal trapping mechanisms for several gas pools. They are not shown on the regional structure map (Pl. 3) because of their small displacements. All of the small faults seem to branch off of a more prominent east–west fault that has displacement of >1,000 ft, down to the south. The small faults in the field have maximum throws of 100–150 ft, up to the south. None of the faults mapped in this study area have recognized formal names. Changes in permeability and/or thickness in the Cromwell and Jefferson sandstones augment the fault traps. A structure map of the study area (Fig. 48) shows the configuration of the top of the Wapanucka Limestone (see type log, Fig. 45). In this area, the top of the "Wap" (commonly used acronym) is consistently ~300 ft above the top of the Cromwell, so it accurately depicts the structural configuration of both units. Other tops such as the Union Valley Limestone or Cromwell could have been used for structural interpretations, but they are not as uniform as the top of the "Wap." The top of the "Wap" is picked at the distinctive thin shale break that separates the Wapanucka Limestone from the overlying limestone and sandstone interval called the Spiro/Wap. Each producing pool in the study area has ~50 ft of closure.

SANDSTONE DISTRIBUTION AND DEPOSITIONAL ENVIRONMENTS

The two principal reservoirs in Raiford SE Field are the Cromwell Sandstone and the Jefferson sandstone. Only the upper Jefferson is a consistent producer; the Cromwell produces in only five wells in the study area. Figures 49–52 are isopach maps depicting the gross and net sandstone thicknesses for both of these reservoirs.

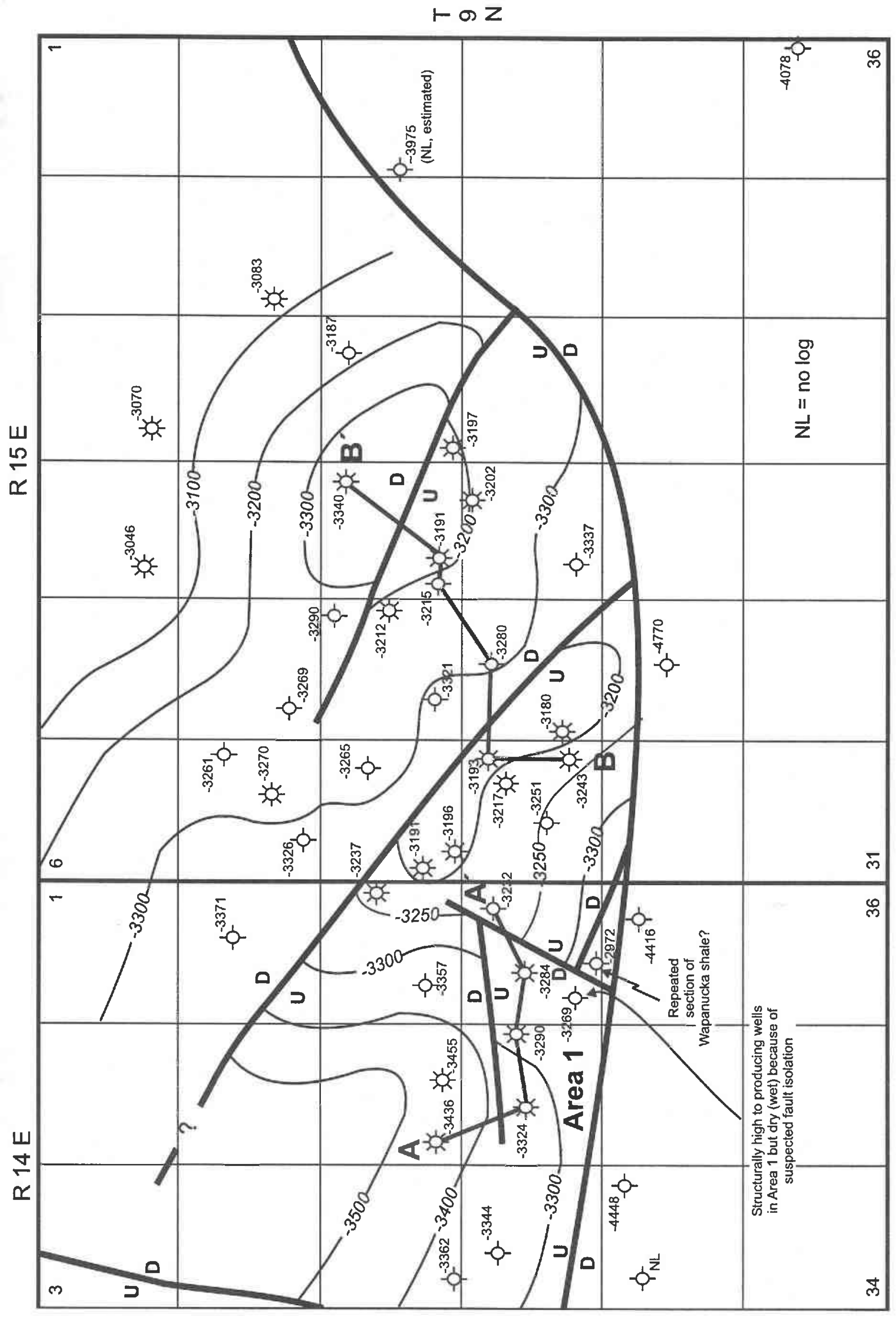


Figure 48. Structure map depicting the top of the Wapanucka Limestone, Raiford SE Field, south-central McIntosh County, Oklahoma. Contour interval is 100 ft. Datum is mean sea level. See Figure 44 for well names.

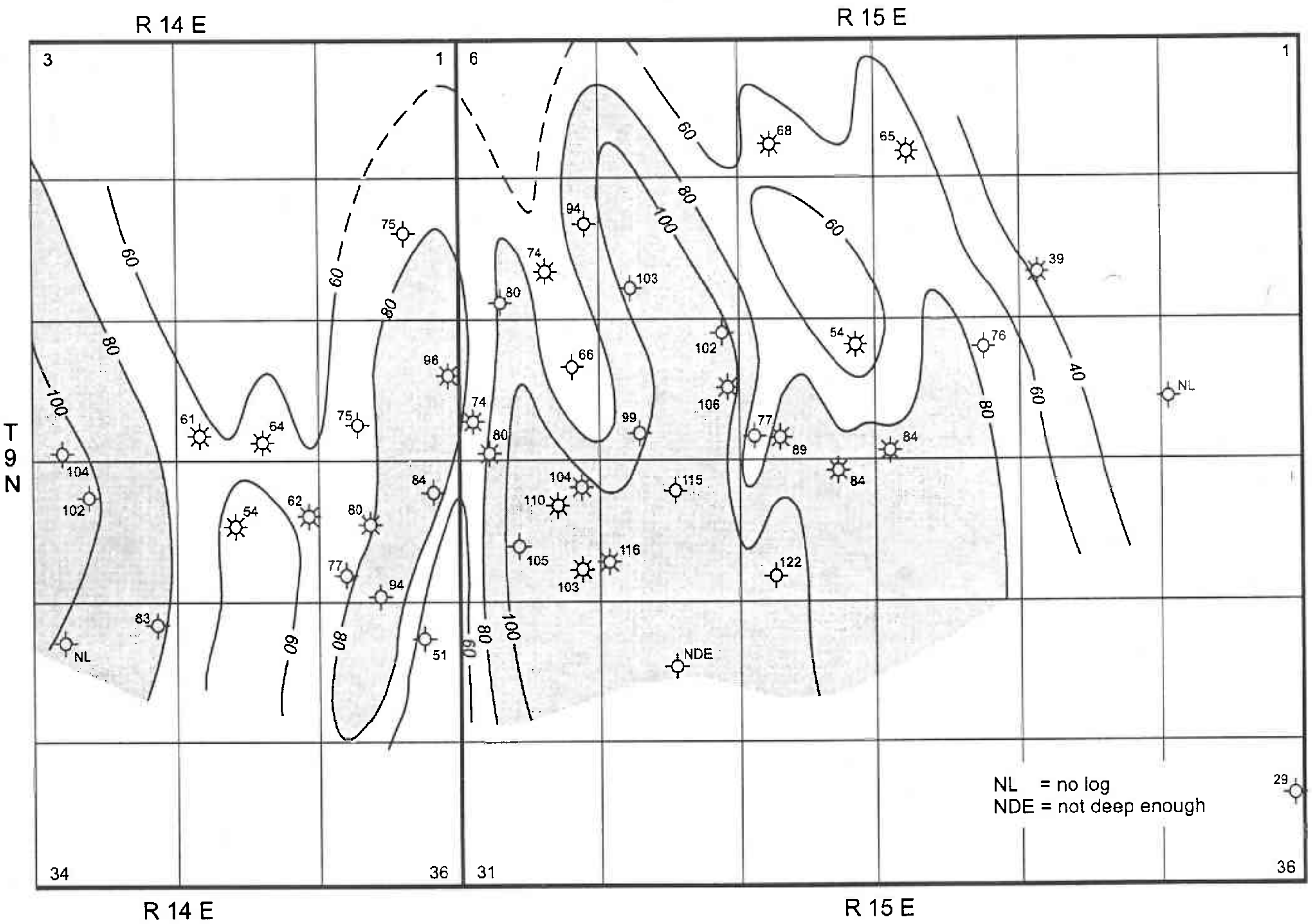


Figure 49. Gross isopach map of the Cromwell Sandstone (undifferentiated) in Raiford SE Field, south-central McIntosh County, Oklahoma. Contour interval is 20 ft. See Figure 44 for well names.

Cromwell Sandstone (Figures 49, 50)

The Cromwell Sandstone interval consists of as many as three distinct sandstone zones that are separated by shale beds a few feet to several feet thick. In some places, thicker sandstone zones split and thinner zones coalesce. Elsewhere, all the sandstone zones coalesce to form one essentially massive sandstone interval. That variability makes detailed correlations within the Cromwell somewhat conjectural, so individual sandstone zones are not mapped separately in this study.

Figure 49 shows the gross thickness of sandstone in the entire Cromwell Sandstone interval for all the wells in the study area. The gross thickness is the amount of sandstone regardless of porosity, as determined from the 50% sand/shale line on gamma-ray logs and does not include shale breaks. The spatial distribution of gross Cromwell Sandstone as defined and mapped in this study is not always relevant to where gas is found, nor is there any coincident with structure. It is likely that the isopach of Figure 49 accurately shows the distribution of this sandstone but that significant hydrocarbon trapping takes place farther north beyond the mapped area.

The gross Cromwell Sandstone forms large north–south-trending ridges or bars that laterally adjoin one another. Sandstone thickens basinward to the south where it reaches 122 ft thick but thins northward onto the shelf where it is only ~60 ft thick. Interbar facies between major sandstone ridges typically contains sandstone interbedded with shale, so the total amount of sandstone is reduced in these areas. Where this happens, thickness changes of >50 ft can occur within half a mile. In the eastern part of the study area, the Cromwell sandstone thins to <40 ft because sourcing is more distal. Several townships farther east, the Cromwell becomes increasingly limy and eventually grades into bioclastic limestone that forms much of the Morrowan outcrop in the Ozark Uplift.

Textural patterns (from well logs) and sedimentary structures (from core and outcrops) are the principal lines of evidence for these reservoirs being marine bars. Both features have characteristics that are influenced by depositional processes consistent in a shallow marine environment. For textural log patterns, the nature of the *lower* bar contact is often diagnostic: some bars have gradational lower contacts, whereas other contacts are more abrupt. The explanation is that gradational contacts grade upward from shale at the base to sandstone above and were formed during slow vertical accretion. This textural pattern may indicate that deposition took place in deeper

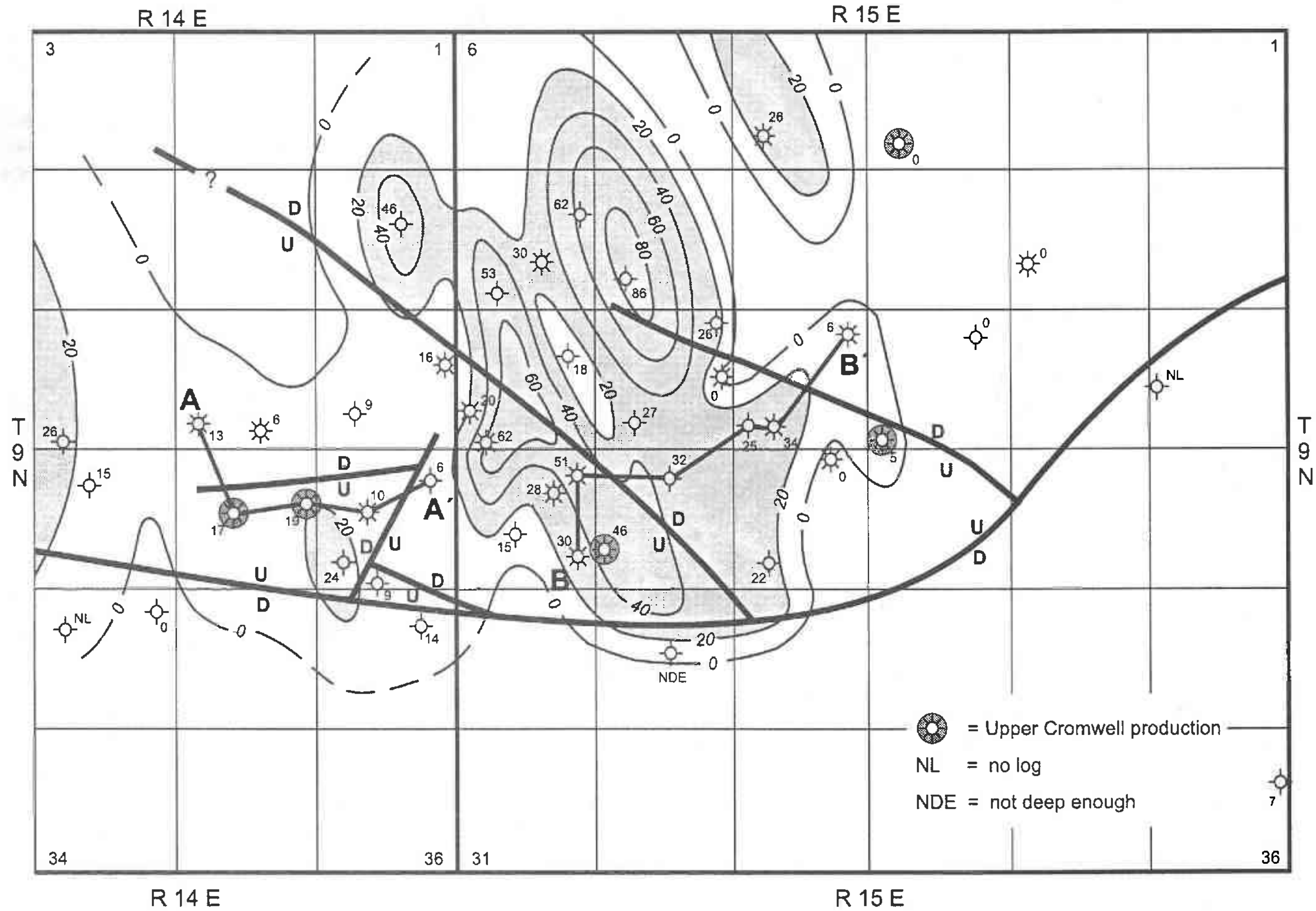


Figure 50. Net isopach map of the Cromwell Sandstone (undifferentiated) in Raiford SE Field, south-central McIntosh County, Oklahoma. Net sandstone has log porosity ≥7%. Contour interval is 20 ft. See Figure 44 for well names.

water farther basinward or that it occurred adjacent to the main bar complex. More abrupt basal contacts probably are indicative of rapid bar deposition, since there is little development of a transition zone. These types of basal bar contacts are more likely to form closer to shore in a sand-rich marine environment where high current energy exists. Both kinds of lower bar contacts characterize the Cromwell in this study area and are shown on log traces in cross sections A–A′ and B–B′ (Figs. 46, 47).

Sedimentary structures are also diagnostic of specific depositional environments and are often correlative to certain bar zones identified from well logs. Scoured bedsets, massive, convolute, high-angle cross bedding, and beds containing transported fossil fragments typically are found in the upper part of a marine bar sequence represented by a "clean" gamma-ray log signature. These facies are indicative of shallow, high-energy environments where deposition is rapid. Other sedimentary structures are common to the Cromwell but originate in a very different marine environment. Ripple bedding, bioturbation, and abundant trace fossils commonly are found in bar transition and lower bar facies that typically are represented by a transitional gamma-ray log signature beneath the upper bar facies. These facies generally indicate slower, more uniform, non-destructive, and in some situations, slightly deeper water deposition.

Figure 50 shows the thickness of net Cromwell Sandstone having porosity ≥7% for all the wells in the study area. This cutoff is believed to be close to the lower limit of sandstone porosity necessary for gas production in this area. Porosity values were determined by visually averaging the cross-plot porosity on density-neutron logs. No adjustments were made to account for logs recording porosity based on a limestone matrix (density of 2.71 g/cm^3). In the absence of a neutron log, density-porosity determinations were made by multiplying the observed density porosity by a factor of <1.0 (usually ~0.7) to account for the gas effect on the density log. The average thickness of productive net sandstone is probably a little less than 20 ft.

Areas of thick net Cromwell Sandstone coincide with the north ends of thick gross sand accumulations (Fig. 49). In these areas, the Cromwell Sandstone is as much as 86 ft thick, but it is usually <40 ft thick. Isolated zones have porosity reaching 7–11% net, whereas most of the remaining Cromwell is tightly cemented with carbonate material and has porosity of only 4–6%, which is below what is necessary to produce in this area. Interbar facies contain substantial interstitial clay and interbedded shale, which also reduces porosity and the amount of net sandstone. The net/gross sandstone relationship can be seen by comparing the gamma-ray and porosity responses on

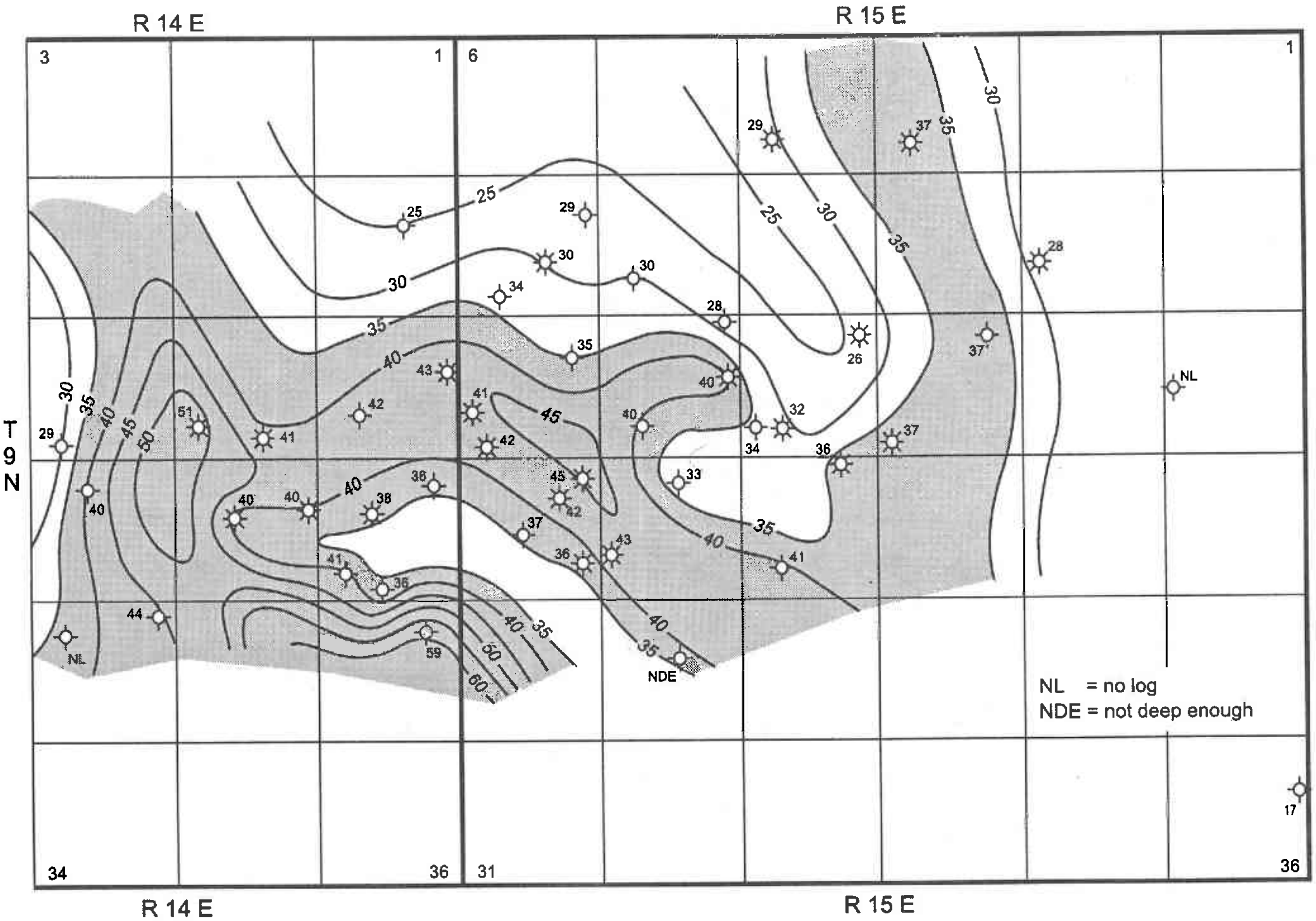


Figure 51. Gross isopach map of the upper Jefferson sandstone (Lower Cromwell?) in Raiford SE Field, south-central McIntosh County, Oklahoma. Contour interval is 5 ft. See Figure 44 for well names.

any of the logs in cross sections A–A′ and B–B′ (Figs. 46, 47). Generally, sandstone zones containing the highest porosity are found within the thickest sandstone sequences and probably signify different depositional episodes.

The Cromwell Sandstone is productive in five wells in the study area (Fig. 43). Two of these wells are in producing Area 1, where the trap may be caused by faults. Three other Cromwell producers are scattered throughout the study area, and none of them appear to relate directly to the distribution of net sandstone as mapped in Figure 50. For the Cromwell in this study area, it is unusual that thick sandstone trends cross fault boundaries without entrapment of hydrocarbons. The highest-volume Cromwell well in Area 1 produced a little more than 0.5 BCFG. The Cromwell is wet or tight throughout most of this study area.

Upper Jefferson Sandstone (Figures 51, 52)

The upper Jefferson sandstone is the first sandstone sequence below the low resistivity Springer shale. In Raiford SE Field this sandstone varies in thickness from ~25 ft in the north to almost 60 ft in the south and seems to be distributed in bars trending both east to west and north to south (Fig. 51). The gross sand thickness is picked from the 50% sand/shale line on gamma-ray logs without respect to porosity and does not include interbedded shale.

Reservoir quality is variable within the field and may be related to faulting. Porosity reaches 12–13% in some zones and is frequently more than 8–10% with strong density-neutron crossover. But the same zone may become tightly cemented with carbonates within a mile, reducing porosity to less than 5–8%. Log characteristics of productive upper Jefferson reservoirs include a significant SP deflection, porosity of ≥7%, and resistivity >30 Ω. Gas production is probably negligible in sandstone having <7% porosity, the lower limit of porosity in the net sandstone map (Fig. 52). When porosity in the lower Jefferson sandstone is very low, it can be difficult to distinguish from limestone on well logs. Overall, the areal extent of net upper Jefferson sandstone conforms nicely to the production allocation of this reservoir.

The upper Jefferson sandstone typically has a blocky log shape, because the lower and upper contacts grade rapidly into shale. This is best illustrated on gamma-ray logs but is also definitive on resistivity and porosity logs. The coarsening upward textural profile that is characteristic of marine bars is generally lacking for this sandstone interval in this field. The relatively sharp basal contacts probably formed in response to rapid deposition during storm events. Fluvial channeling is not identified in the

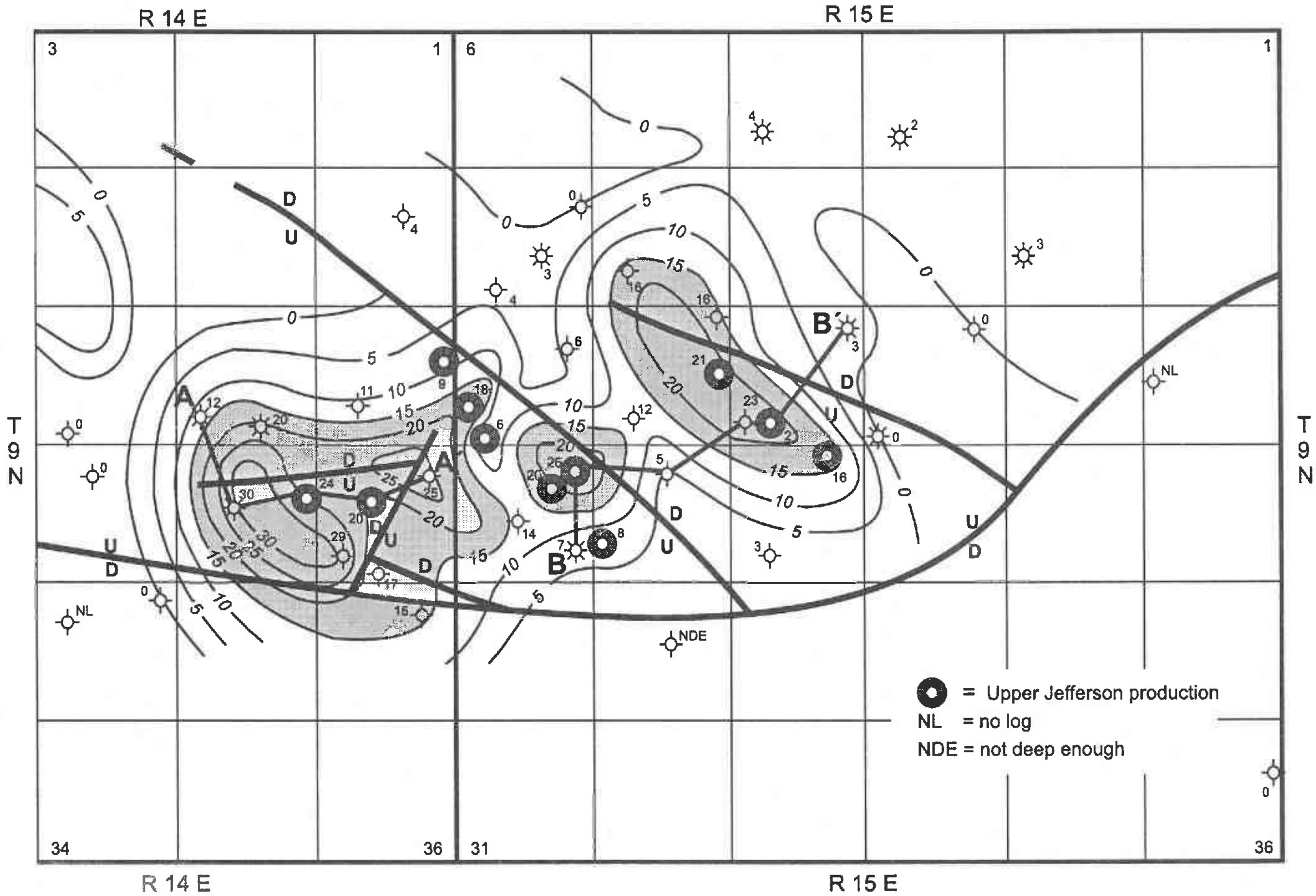


Figure 52. Net isopach map of the upper Jefferson sandstone (Lower Cromwell?) in Raiford SE Field, south-central McIntosh County, Oklahoma. Net sandstone has log porosity ≥7%. Contour interval is 5 ft. See Figure 44 for well names.

upper Jefferson sandstone. The absence of distinct and isolated bars is indicative that the depositional environment was close to shoreline where stronger currents and local sand supply prevailed. In more distal shelf environments, sandstone is often segregated into discrete bars that are encapsulated in shale.

Lower Jefferson Sandstone (Figures 53, 54)

The lower Jefferson sandstone is separated from the upper Jefferson interval by about 20–30 ft of very low resistivity shale. It occurs in two main zones, the lower being the thickest and more porous, although either is productive locally. The thickest and most porous sandstone is in the central and western parts of the study area and is most productive within Area 1 (Fig. 53). Both zones thin to the north and east and thicken to the south. Unlike the upper Jefferson, gross sandstone in the lower Jefferson interval occurs in more-or-less discrete north–south-trending bars with an aggregate thickness locally exceeding 25 ft (Fig. 53). Log shapes in both sandstone zones almost always have a coarsening-upward textural profile that is indicative of gradual vertical accretion in a marine bar. The lower Jefferson bars are generally <1 mi wide and 1–3 mi long.

The lower Jefferson sandstone in Raiford SE Field generally has low porosity and permeability. This is indicated by cross plot porosity on density-neutron logs and by the weak SP response. A few wells have good porosity of 8–12%, and all of them are in producing Area 1 (Fig. 54). The maximum net sandstone thickness is 12 ft, but where productive it is always ≤10 ft thick. Most of the study area is devoid of net sandstone.

The few wells producing from the lower Jefferson are either high on structure or near the updip limit of porosity. In those wells the porosity is generally >7% and true resistivity is >30 Ω. SP deflections are not as pronounced as those in the Cromwell or upper Jefferson, due to the thinness and low permeability of the sandstone.

CORE ANALYSIS

There are no core analyses available from either the Cromwell or Jefferson wells in Raiford SE Field. Several core analyses of the Cromwell Sandstone are available from Deep Rock wells 20 mi to the west in Ts. 6–7 N., R. 10 E. (Figs. 22, 23 [Part I]). Those analyses indicate that sandstone with porosity of 10% has permeability of between 1 and 10 milidarcies. Sandstone with porosity of 14% has permeability of 20 to >100 milidarcies. These values probably are applicable to the Cromwell Sandstone in Raiford SE Field.

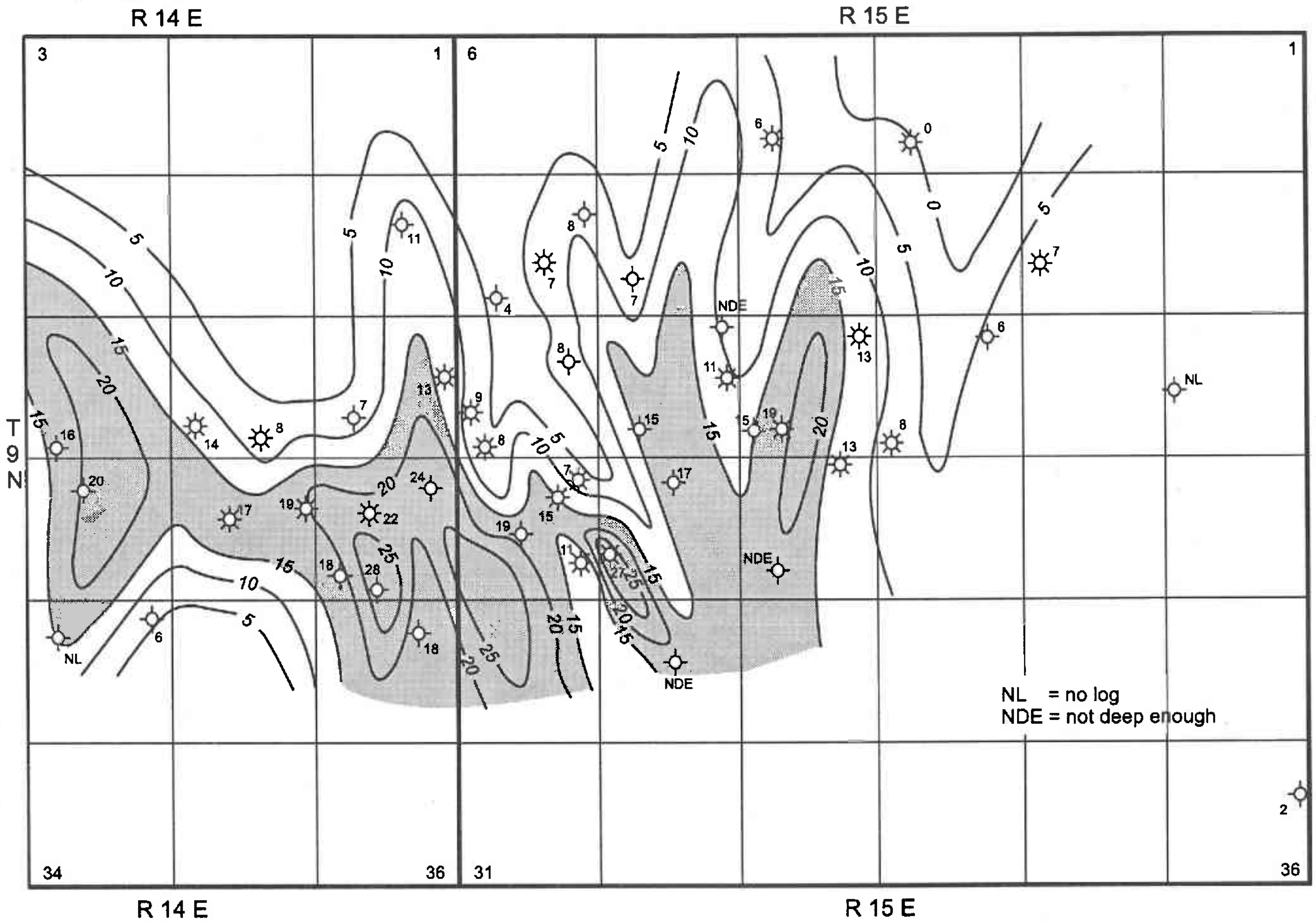


Figure 53. Gross isopach map of the lower Jefferson sandstone interval in Raiford SE Field, south-central McIntosh County, Oklahoma. Contour interval is 5 ft. See Figure 44 for well names.

FORMATION EVALUATION

Correlation of the principal reservoirs throughout Raiford SE Field is relatively easy. Therefore, data used in reservoir evaluation of either the Jefferson or Cromwell including sandstone thickness, porosity, water resistivity, and formation resistivity are all factors that are easily determined and applicable to a specific reservoir throughout the field. For the most part, interstitial clay does not seem to interfere with water saturation calculations or determining reservoir parameters for either the Cromwell or Jefferson.

Cromwell Sandstone is typically very clean except for the ubiquitous carbonate and silicate cementation. This is apparent on gamma-ray logs by the low response across sandstone intervals. In the absence of significant formation clay, values of true formation resistivity (R_t) taken directly from well logs leads to plausible calculated water saturation (S_w) values in most reservoir conditions, whether water-wet or hydrocarbon-saturated. Notation of R_w values were sometimes indicated on logs from service company calculations, although their value of 0.04 ohm-meters (Ω) resulted in S_w values that were consistently too high. Experimentation with different R_w values was necessary to more realistically characterize water-wet and hydrocarbon zones. Finally, an R_w of 0.03 Ω was decided upon, which resulted in relatively realistic values of S_w when considering both saturated and wet zones. This is the same value used in Scipio NW Field (Part II).

The deep, or true, resistivity (R_t) of producing sandstone in the Cromwell Formation typically ranges from 30 Ω to a little more than 200 Ω. A deep resistivity of <25 Ω almost always indicates that the zone is wet unless porosity is anomalously high or the zone is depleted. Very low resistivity of <5 Ω certainly indicates water saturation near 100%. With a typical porosity of 6–10% the Jefferson or Cromwell probably won't produce significant gas with resistivity of <40 Ω. Relatively high resistivity in sandstone zones having <6% porosity is usually attributed to matrix effects rather than hydrocarbons (see field cross sections, Figs. 46 and 47). Extremely high resistivity, >200 Ω, in the absence of net porosity indicates the formation is tightly cemented, usually with carbonates.

Characterization of permeability and porosity by examining the separation between the shallow and deep resistivity curves seems to be an effective technique of quickly interpreting sandstone quality for both the Cromwell and Jefferson sandstone. This method is based on the assumption that the amount of invasion of drilling fluids is proportional to the porosity and permeability of the reservoir, and that the amount of separation between the shallow and deep resistivity curves is affected by the degree of invasion. The upper Jefferson and, to a lesser extent, the Cromwell are likely to have good resistivity separation in porous zones, whereas this effect is generally not the case for the lower Jefferson. This effect is best illustrated on detailed resistivity logs that are not included in the field cross sections.

Porosity determinations were made by taking the crossplot porosity of the density and neutron logs. Porosity values in the "cleanest" part of the producing sandstone intervals ranged from 3% to 13%, commonly 5–10% for the Cromwell Sandstone and 6–12% for the upper Jefferson sandstone. Logging companies routinely combine density-neutron tools and compute porosity using a matrix density of 2.71 g/cm^3 (limestone) or 2.68 g/cm^3 (limy sandstone). Deriving porosity using the higher matrix density (2.71) theoretically results in values a few percentage points too high, whereas using the lower matrix density (2.68) results in more accurate porosity values. This occurs because most Cromwell and Jefferson sandstone has carbonate cement. Porosity values used in this study were pessimistically estimated to take into account a limestone matrix density (2.71) but were not reduced by two to three percentage points as some log analysts do. When only density porosity was available, values were reduced by multiplying the indicated density porosity by a fraction, usually ~0.7, so that the resulting porosity accounts for some of the normal gas effect in producing wells that causes the density porosity to be too high. Gas effect (crossover) in productive intervals is consistently 5–10 porosity units but may be much less in tight sandstone. Extremely large separations of 14–18 porosity units are thought to be due to pressure depletion. Gas effects can be seen on the accompanying well logs of cross sections A–A′ and B–B′ (Figs. 46, 47).

Water saturation (S_w) calculations for the Cromwell and Jefferson are extremely variable and range from 14% to 93% (Table 6). In producing zones, calculations normally indicate S_w is <40%, although some productive zones may have unrealistically high S_w in excess of 50%. In these situations S_w values probably are correct but include water bound in shale rather than free (mobile) water in sandstone. Similarly, cementation is blamed for unrealistically high S_w values in tight zones, because the formation factor (F) in the numerator of the S_w formula gets very large.

Calculations were made by using the equation $S_w = \sqrt{(F \times R_w) / R_t}$. The value for formation water resistivity (R_w) that proved to best fit the reservoir conditions is 0.03 Ω at

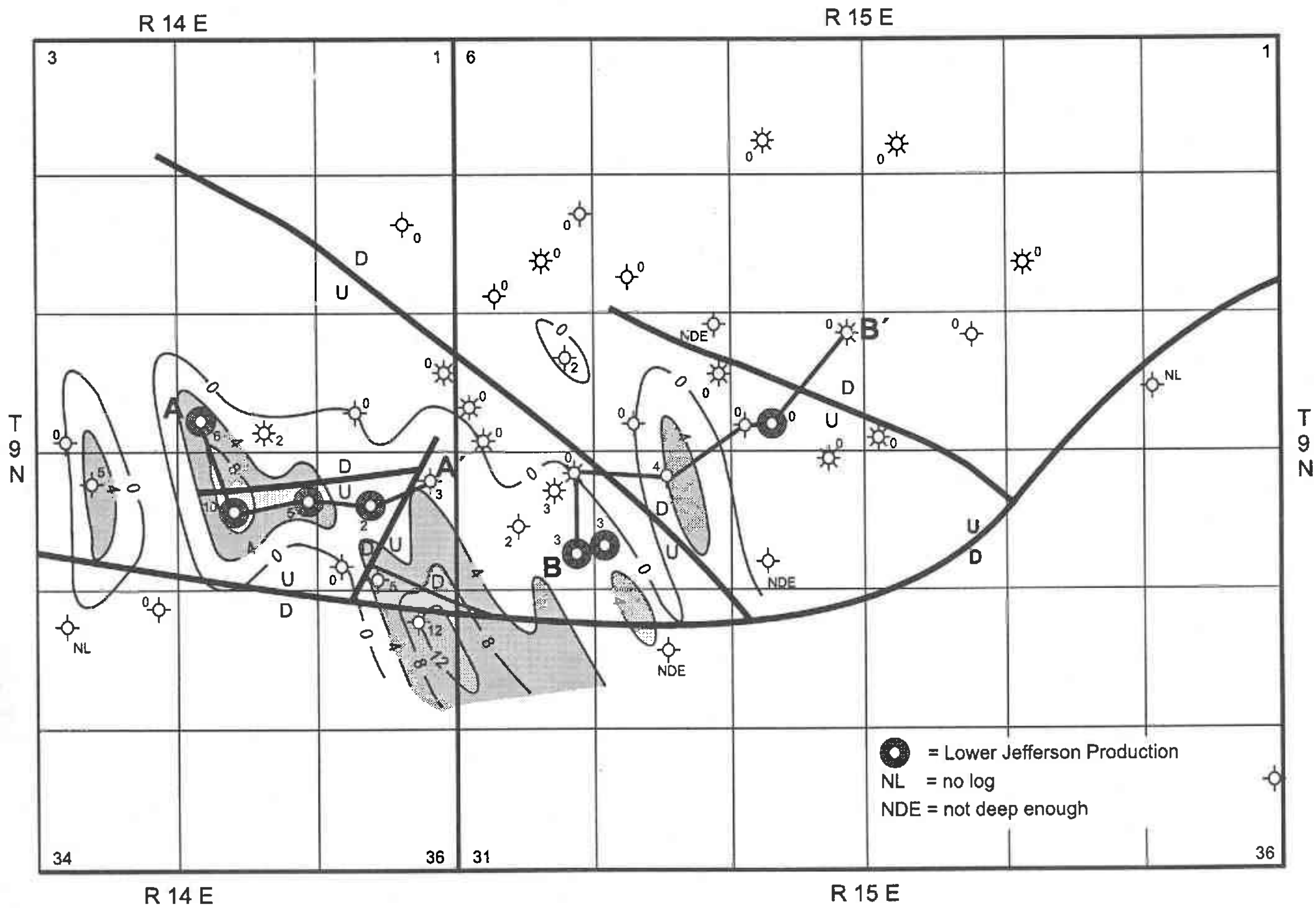


Figure 54. Net isopach map of the lower Jefferson sandstone interval in Raiford SE Field, south-central McIntosh County, Oklahoma. Net sandstone has log porosity ≥7%. Contour interval is 4 ft. See Figure 44 for well names.

formation temperature. The Archie equation for formation factor ($F = 1/\phi^2$) was not used because calculations resulted in unrealistically low hydrocarbon saturation values. Therefore, the modified equation ($F = 0.81/\phi^2$) was used with satisfactory results in calculating S_w. Values for true resistivity (R_t) were taken directly from the deep resistivity logs without much concern for clay effects. Clay affects R_t calculations when water in clays is erroneously considered part of the mobile formation water. Porosity values also were taken directly from density-neutron or density logs in a manner described above. The few wells that had only sonic logs, the acoustic travel time used to determine whether or not sandstone had net porosity was ~66 microseconds/ft. This value was arbitrarily selected because of formation gas effects and the presence of shale and/or interstitial clay. Reservoir characteristics pertaining mostly to the upper Jefferson sandstone in Raiford SE Field are summarized in Table 7. In this study, a spreadsheet was created incorporating representative values of R_t and cross-plot porosity at a specific depth, which then were used to calculate S_w (Table 6).

OIL AND GAS PRODUCTION

Cumulative gas production from the Cromwell Sandstone and the Jefferson sandstones in all three areas of Raiford SE Field is estimated to be 10.3 BCF from 1961 through February 2002. Most of this production comes from seven wells in Area 2 (7.3 BCFG), which produces largely from the upper Jefferson sandstone. Area 3 also has produced significant gas (2.1 BCF), mostly from the upper Jefferson. Area 1, however, produced only 0.9 BCFG, and this was about evenly distributed between the Cromwell and Jefferson. In most wells in all the areas, the gas production is commingled between the Cromwell, Jefferson, and Hunton, so production allocation for individual zones is hard to determine. Many of the wells within this field are still active. Figure 55 shows cumulative gas production for each well in the study area.

Figure 55 also shows the date of first production, initial production (IP), flowing tubing pressure (FTP), shut-in tubing pressure (SITP), and bottom-hole pressure (BHP) if that information is known. By comparing the date of first production to cumulative production, it is obvious that wells completed earliest produced the most gas, because they encountered virgin or close to virgin reservoir pressure and have been on line longest. There is good pressure communication in most upper Jefferson reservoirs, so recently drilled wells always encounter pressure depletion. No liquids were produced from the Cromwell or Jefferson in this field.

On the basis of volumetric calculations, the gas produced from the upper Jefferson in Area 2 represents 96% of the original recoverable gas in place, which is estimated to have been 7.6 BCF (502 MCF/acre ft) (Table 7). The high recovery probably is accurate because all the wells are pressure depleted and that gas largely was produced from one reservoir. These values are significantly different from those for the upper Jefferson in Area 3, which are estimated to be only 65% (211 MCF/acre ft). Pressure depletion also prevails in Area 3, but the low recovery may be due to undrained areas in the center part of the pool immediately south of the bounding fault.

Since gas production from the lower Jefferson sandstone is commingled with higher potential reservoirs, the actual recovery from this reservoir is unknown. One well in the SW¼ sec. 14, T. 9 N., R. 14 E., produced 862 MMCFG entirely from the lower Jefferson. The reservoir in that well is unusually thick and porous, so it is unlikely that the lower Jefferson in other areas would be as good. Overall, the lower Jefferson is a poor-performing reservoir.

The better wells in Raiford SE Field all produce from the upper Jefferson sandstone and are located in structurally high positions within their respective fault blocks. The better wells encountered virgin or near-virgin pressures of ~2,000 PSI and had above average reservoir thicknesses. The highest volume well in the entire study area produced 3.4 BCFG in Area 2; other good wells had cumulative production of 2.3 BCF, 1 BCF, 0.95 BCF, and 0.58 BCF, and several wells made less gas than that. One well producing solely from the Cromwell in Area 3 produced 0.63 BCFG. Recently drilled wells find the Cromwell and Jefferson reservoirs depleted.

The initial production potential from early wells was often calculated assuming absolute open-flow without choke. The subsequent production rate was referred to as "gauged," and rates varied from 500 MCF to 5.7 MMCFGPD. Actual measured initial production (IP) rates were much lower. Most wells had IPs of <500 MCFGPD, but a few came in for 2 to >3 MMCFGPD. In the early wells the initial shut-in tubing pressures (SITP) varied between 1,850 and 1,950 PSI, but that pressure had fallen to 400–900 PSI in wells drilled during the 1990s. Flowing tubing pressure (FTP), when compared to SITP, is an indication of reservoir quality. The closer the two pressures are to each another, the better the reservoir performance is, and when those pressures are unalike the reservoir is tight. Pressure data for most wells in Raiford SE are incomplete, so this ratio cannot be determined for those wells. Limited data from early wells indicate the FTP/SITP ratio was originally ~0.7. More recent wells have a ratio of 0.2–0.5. The only good well that produced solely from the lower Jefferson had a ratio of 0.8.

PRODUCTION-DECLINE CURVES (Figures 56, 57, and Table 8)

Production-decline curves for four wells that have good pressure and production histories are shown in Figures 56 and 57. Figure 56 shows the decline curve for two upper Jefferson wells, one in Area 2 and one in Area 3. Figure 57 shows the decline curves for a Cromwell well in Area 3 and a lower Jefferson well in Area 1. The production and pressure data used to construct these curves are included in Table 8.

Both curves in Figure 56 show that the initial reservoir pressure in the upper Jefferson was ~2,000 PSI, and subsequent production lowered it to several hundred PSI. The Hall-Jones 1-Woods well shown in the upper curve produced gas from Area 3 and had 21 ft of net upper Jefferson sandstone. The lower part of that sandstone contained a gas/water contact and was wet. The production decline appears relatively normal from first production in 1961 through 1975. Thereafter, a rapid decline set in until

TABLE 6. — Well Information Sheet Identifying Formation Tops and Sandstone Thickness,

S3	S2	S1	SEC	Status	Operator	Lease	Well #	Comp date	ELEV	TD	Perforated interval	Wapanucka Limestone		Union Valley Limestone		Cromwell & Upper Jefferson	
				Hart=Hartshorne; W=Wapanucka; C=Cromwell undifferentiated; UJ=Upper Jefferson; LJ=Lower Jeferson; Mz=Misener; H=Hunton								top	subsea	top	subsea	net 7%	gross
T. 9 N., R. 14 E.																	
	C	Se	4	Dry	Hold Oil	Fisher	2	Nov-86	876	4210		3650	-2774	3800	-2924	31	107
	C	Sw	4	Dry	Grace Petroleum	Fisher	1	Apr-80	748	4275		3665	-2917	3850	-3102	42	118
	Sw	Ne	12	Dry		Rule	1	Jun-78	621	5050		3992	-3371	4232	-3611	50	100
	Ne	Sw	13	Dry	Man & Wood	Cosar	1	May-61	725	5200		4082	-3357	4276	-3551	20	117
	Se	Ne	13	**Gas, UJ, H**	Hall LJones	LJaneway	1	Jul-62	626	4919	4278-4305; 4830-47	3863	-3237	4050	-3424	25	139
	Sw	Se	14	Gas, GiULJrease	Hold Oil	Fisher	1	Jun-86	743	4796		4198	-3455	4336	-3593	26	105
	Sw	Sw	14	**Gas, LJ**	Wenexco	Fisher	1	Apr-81	832	4928	4791-97	4268	-3436	4460	-3628	25	112
	Sw	Sw	15	Dry	Wenexco	Fisher	1	Mar-81	848	5425		4210	-3362	4400	-3552	26	133
	E/2	Nw	22	Dry	TXO	Fisher	1	Feb-88	856	5400		4200	-3344	4396	-3540	15	142
	Se	Ne	23	**Gas, C, LJ, H?**	TXO	Skinner	1	Jul-79	707	5200	4327-4528 gross	3997	-3290	4190	-3483	43	102
	Se	Nw	23	**Gas, C, LJ**	TXO	Sharp	1	Feb-81	722	4650	4377-4460; 4558-61, 4570-82	4046	-3324	4237	-3515	47	94
	Sw	Sw	24	Dry	Scout Energy	Abel	1	May-85	801	5300		4070	-3269	4270	-3469	53	118
	Se	Nw	24	**Gas, ULJ**	Marlin Oil	Carpenter	1	Sep-90	690	5800	4411-13	3974	-3284	4167	-3477	30	118
	Ne	Ne	24	Dry	Southern Union	Dover	1	May-58	662	5020		3894	-3232	4093	-3431	31	120
	Se	Sw	24	Dry	Deep Rock Oil	Selfridge	1 "A"	Oct-52	836	5482		3808	-2972	4322	-3486	26	130
	C	Ne	25	Dry	Lubell Oil	Skinner	1	Feb-81	644	5665		5060	-4416	5314	-4670	30	110
	Ne	Ne	27	Dry	Wenexco	McCullar	1	Feb-81	670	5725		5118	-4448	5273	-4603		127
	C	Nw	27	Dry		Brotton	1	Jan-47		4238		No logs		No logs			
T. 9 N., R. 15 E.																	
	C	Sw	3	**Gas, C, UJ**	Grace Pet	Goodsell	1	Oct-80	627	4870	4034-38; 44-48; 4150-65	3697	-3070	3970	-3343	2	102
	C	Sw	4	Gas, Atoka	Hold Oil	Ewens	1	Feb-84	646	4850	2951-63	3692	-3046	absent		30	97
	S/2	Sw	7	Dry	TXO	Lawson	1	Feb-80	654	5110		3980	-3326	4229	-3575	57	114
	Nw	Se	7	Gas, H	Hall-LJones	Martin	1	Jun-62	692	5050		3962	-3270	4220	-3528	33	104
	Se	Ne	7	Dry	SK Resources	Fisher	1	May-84	668	5005		3929	-3261	4180	-3512	62	123
	C	Sw	8	Dry	Hunton Gas	Fisher	1	Jul-87	850	5200		4119	-3269	4365	-3515	102	133
															0		
	Nw	Sw	11	Gas, Booch	Western Wells	Dyas	1	Oct-77	625	4820		3708	-3083	absent		3	67
	Nw	Sw	13	Dry	Stanolind	Tiger	1	Nov-36	660	5007	No Logs	NL					
	Sw	Sw	15	**Gas, C**	LJ.C. Man	Turley	1	Apr-62	600	4920	4145-48, 4154-62	3797	-3197	4067	-3467	5	121
	N/2	Ne	15	Dry	Coquina Oil	Chenault	1	Dec-75	619	4972		3806	-3187	absent			113
	Ne	Ne	16	Gas, Atoka	Leede Oil	Vivian	1	Dec-80	634	5060		3974	-3340			9	80
	Sw	Sw	16	Dry	XAE Corp	Farrow	1	Oct-97	619	4971		3834	-3215	4090	-3471	48	111
	Se	Sw	16	**Gas, UJ, LJ, H**	Southern Union	Brown	1	Jul-59	589	4865	4203-33; 4283-90	3780	-3191	4052	-3463	55	121
Ne	Ne	Ne	17	Dry	Flynn Oil	Woods	1	Sep-49	600	4386		3890	-3290	4132	-3532	42	130
	Se	Sw	17	Dry	Southern Union	Woods	1	Jul-60	686	4555		4007	-3321	4260	-3574	39	139
	Se	Ne	17	**Gas, UJ, Mz, H**	Hall-LJones	Woods	1	Dec-60	642	4962	4290-316	3854	-3212	4106	-3464	21	146
	Nw	Sw	18	**Gas, UJ, H**	Carter Oil	Follansbee #1	11-50 Carter Oil(dry)[1]		661	5461	4280-4300	3852	-3191	4054	-3393	38	115
	Sw	Sw	18	**Gas, Hart, UJ, H**	XAE Corp	McQuay	1	Nov-94	634	4804	4254-64	3830	-3196	4076	-3442	68	122
	Se	Ne	18	Dry	Southern Union	Green	1	Apr-56	675	4975		3940	-3265	4190	-3515	24	101
Ne	Ne	Sw	19	Dry	Ward Edinger	Crabtree	1	Dec-60	633	4999		3884	-3251	4100	-3467	29	142
		Ne	19	**Gas, UJ**	Southern Union	Bartleson	1	Feb-58	591	4965	4252-72	3808	-3217	4010	-3419	48	152
	Ne	Ne	19	**Gas, UJ**	Sonat	Kimberling	2	Jun-92	620	5100	4256-98	3813	-3193	4462	-3842	77	149
	E/2	Se	19	**Gas, Booch, LJ**	TXO	Kimberling	1	Mar-90	707	4146	4483-89	3950	-3243	4168	-3461	37	139
	Nw	Sw	20	**Gas, C, UJ, LJ**	Earlsboro	Brotten	1	Jan-63	700	5088		3880	-3180	4101	-3401	54	159
	Nw	Ne	20	Dry	Petroleum Inc.	LJaneway	1	Aug-61	670	5050		3950	-3280	4213	-3543	37	148
	Se	Sw	21	Dry		Turley	1	Sep-63	675	4518		4012	-3337	4260	-3585	25	163
	N/2	Ne	21	**Gas, UJ**	Southern Union	Turley	1	Feb-61	628	4961	4274-92	3830	-3202	4103	-3475	16	120
Sw	Sw	Ne	29	Dry	Mason Company	Creek Tribe	1	Feb-62	620	5780		5390	-4770	5640	-5020		
Se	Se	Ne	36	Dry	Western Diversified	Conners	1	Nov-72	612	5500		4690	-4078	5015	-4403	7	46

Note: Highlighted rows indicate Cromwell or Jefferson production in study area.

abandonment in 1983. During the 24-year life of that well it produced 945 MMCFG. The rapid decline in annual production during the last several years was not apparently accompanied by a corresponding rapid drop in reservoir pressure, possibly an indication that the well simply watered out. A half mile to the southeast, the Southern Union 1-Brown (the closest completed well [not graphed]) experienced a rapid decline in pressure beginning in 1969, 6 years before the rapid decline set in in the Woods well. This indicates that the reservoirs in the two wells are separate or have poor communication.

The bottom curve in Figure 56 shows the decline of the Southern Union 1-Bartleson well in Area 2. That well produced almost 3.4 BCFG over a 27-year history. The net upper Jefferson sandstone in that well is 20 ft thick and is completely gas saturated. Production increases occurred in 1971 and 1976 followed by 3 years of normal decline. Thereafter, annual production stabilized during the last 7 years. The pulses of increased production did not materially affect the reservoir pressure, which declined initially and then stabilized over the last 15 years of production. By 1980 the reservoir pressure in both the Woods and the Bartleson wells had essentially stabilized between 450 and 800 PSI.

The decline curves in Figure 57 represent two different reservoirs in Raiford SE Field. The upper curve illustrates

and Computed Water Saturation for Wells in Raiford SE Field

Sw=((FxRw)/Rt) When Rw = .030 F=.81/por												When Rw = .030 F=.81/por Sw=((FxRw)/Rt)												When Rw = .030 F=.81/por							
Upper Cromwell Sandstone												Upper Jefferson *(formerly Lower Cromwell)* Sandstone												Lower Jefferson Sandstone							
Sandstone					max		max	F	F	Sw	Sw	Sandstone					max		max	F	F	Sw	Sw	Sandstone					max	F	Sw
top	subsea	net 7%	gross	Por	ohms	Por	ohms					top	subsea	net 7%	gross	Por	ohms	Por	ohms					top	subsea	net 7%	gross	Por	ohms		
3902	-3026	25	75									4004	-3128	6	32									4072	-3196	0	5				
3960	-3212	23	77									4075	-3327	19	41									4152	-3404	0	4				
4302	-3681	46	75									4414	-3793	4	25									4476	-3855	0	11				
4395	-3670	9	75									4524	-3799	11	42									4595	-3870	0	7				
4164	-3538	16	96									4278	-3652	9	43									4350	-3724	0	13				
4468	-3725	6	64									4578	-3835	20	41									4646	-3903	2	8				
4591	-3759	13	61									4694	-3862	12	51									4778	-3946	6	14				
4510	-3662	26	104									4661	-3813	0	29									4725	-3877	0	16				
4506	-3650	15	102									4649	-3793	0	40									4722	-3866	5	20				
4325	-3618	19	62	5	40	8	80	324	127	49	22	4430	-3723	24	40	5	110	13	2	324	48	30	85	4502	-3795	5	19	8	50	127	28
4376	-3654	17	54	5.5	80	6.5	60	268	192	32	31	4482	-3760	30	40	9	3.5	8.5	5.5	100	112	93	78	4555	-3833	10	17	8	70	127	23
4394	-3593	24	77									4518	-3717	29	41	13	2.2	10	4.8	48	81	81	71	4592	-3791	0	18				
4295	-3605	10	80	8	20			127		44		4409	-3719	20	38	11	20	9	10	67	100	32	55	4478	-3788	2	22	5	60	324	40
4212	-3550	6	84									4330	-3668	25	36									4396	-3734	3	24				
4450	-3614	9	94									4562	-3726	17	36									4628	-3792	5	28				
5398	-4754	14	51									5496	-4852	16	59									5611	-4967	12	18				
5384	-4714	0	83									5532	-4862	0	44									5604	-4934	0	6				
No logs												No logs												No logs							
4032	-3405	0	65									4142	-3515	2	37									Absent?		0	0				
4004	-3358	26	68									4083	-3437	4	29									4150	-3504	0	6				
4280	-3626	53	80									4400	-3746	4	34									4476	-3822	0	4				
4280	-3588	30	74									4392	-3700	3	30									4456	-3764	0	7				
4218	-3550	62	94									4357	-3689	0	29									4418	-3750	0	8				
4416	-3566	86	103									4550	-3700	16	30									4610	-3760	0	7				
4013	-3388	0	39									4120	-3495	3	28									4180	-3555	0	7				
4935	-4275		NL									NL			NL									NL			NL				
4083	-3483	5	84	9	160			100		14		4208	-3608	0	37	5	100			324		31		4276	-3676	0	8				
4100	-3481	0	76									4220	-3601	0	37									4285	-3666	0	6				
4258	-3624	6	54									4364	-3730	3	26									4427	-3793	0	13				
4120	-3501	25	77	7	25			165		45		4241	-3622	23	34	9	25	10	12	100	81	35	45	4312	-3693	0	15	4	50	506	55
4072	-3483	34	89									4200	-3611	21	32									4262	-3673	0	19				
4160	-3560	26	102									4312	-3712	16	28									NDE							
4298	-3612	27	99									4440	-3754	12	40									4508	-3822	0	15				
4146	-3504	0	106									4287	-3645	21	40	8	140			127		16		4356	-3714	0	11				
4160	-3499	20	74	8	50			127		28		4266	-3605	18	41	5	80			324		35		4336	-3675	0	9				
4138	-3504	62	80									4254	-3620	6	42									4324	-3690	0	8				
4253	-3578	18	66									4374	-3699	6	35									4445	-3770	2	8				
4202	-3569	15	105	10	6			81		64		4342	-3709	14	37	10	6			81		64		4410	-3777	2	19				
4100	-3509	28	110									4248	-3657	20	42	8.5	55			112		25		4322	-3731	3	15				
4110	-3490	51	104	11	4.5	7	12	67	165	67	64	4250	-3630	26	45	10	105			81		15		4330	-3710	0	7				
4256	-3549	30	103	6	80	8	9	225	127	29	65	4400	-3693	7	36	8	10			127		62		4470	-3763	3	11	8	60	127	25
4184	-3484	46	116									4330	-3630	8	43									4400	-3700	3	27				
4252	-3582	32	115									4404	-3734	5	33									4470	-3800	4	17				
4300	-3625	22	122	9	4							4452	-3777	3	41	8	8			127		69		NDE							
4124	-3496	0	84									4258	-3630	16	36	10	35			81		26		4328	-3700	0	13				
5707	-5087	NDE										NDE												NDE							
5048	-4436	7	29									5134	-4522	0	17									5186	-4574	0	2				

the decline of production in the only known single-zone completion in the lower Jefferson sandstone. In that well, the National 1-14 Fisher, the initial reservoir pressure was ~1,900 PSI and declined to <100 PSI at abandonment 18 years later in 2001. The Fisher well produced 862 MMCFG from 6 ft of net sandstone.

The lower curve in Figure 57 illustrates the decline of production in the only known single-zone completion in the Cromwell Sandstone in this field. In the Gose & Man 1-Turley well, the Cromwell produced 634 MMCFG over 19 years. The reservoir is only ~5 net ft thick in the well, but it thickens to >30 ft less than a mile to the northwest. The Cromwell gas there was trapped by a combination of faulting and lateral permeability changes.

Pressure versus cumulative production plots of the four wells described in Figures 56 and 57 are shown in Figure 58. They show convergence toward an initial bottom hole pressure of ~2,000 PSI, indicating they all had similar virgin bottom-hole pressures. The shapes of the curves differ, however, from well to well, which indicates differences in the quality and extent of each reservoir.

The upper curve in Figure 58 (designated by triangles) represents production from the upper Jefferson sandstone in the Southern Union 1-Bartleson well of Area 2. At that location the reservoir is relatively thick (20 ft) and laterally extensive. For each PSI drawdown, it produced

TABLE 7. — Reservoir/Engineering Data for the Jefferson Sandstone in Raiford SE Field

	Area 1	Area 2	Area 3
Reservoir	Cromwell, U+L Jefferson	Mostly Upper Jefferson	Mostly Upper Jefferson
Discovery date	July 1979	March 1956	July 1959
Reservoir size—all reservoirs	~280 acres	~1,040 acres	~600 acres
Reservoir volume	individual reservoirs not determined	~14,560 acre-ft	~10,200 acre-ft
Depth	4,400–4,500 ft	4,300–4,400 ft	4,200–4,300 ft
Spacing (gas)	640 with increased density to 320 acres		
Gas/water contact	below −3,740 ft	above −3,700 ft	below −3,650 to −3,670 ft
Porosity in "cleanest" part of sand (most common)	5–13% (~7.5%)	5–10% (7.0%)	6–10% (7.0%)
Permeability	probably 1–30 md	probably 1–25 md	probably 1–30 md
Water saturation (S_w) in producing wells (calculated using R_w = 0.03 ohm-m)	~32%	about 15–35%	about 1–35%
Thickness net sand, ≥7% ϕ for Upper Jefferson (average)	14–25 ft (18 ft)	6–26 ft (14 ft)	16–23 ft (17 ft)
Thickness gross sandstone for Upper Jefferson	36–40 ft	41–45 ft	32–40 ft
Reservoir temperature	~130°F	~130°F	~130°F
Gas density	0.57–0.65	0.57–0.58	0.57–0.58
Z factor (compressibility)[a]	0.86	0.86	0.86
B_g (gas formation volume factor)[b]	~143 std cu ft per reservoir cu ft		
Maximum well-head pressure (PSI)	1,500	1,860	1,950
Initial reservoir press (PSI)	1,649?	2,046	2,057
Initial pressure gradient PSI/ft	0.37?	0.47	0.48
OGIP (volumetric-field)[c]	individual reservoirs not determined	7,600 MMCF	3,336 MMCF
Cumulative field gas (est. to Feb. 2002)	876 MMCF	7,313 MMCF	2,156 MMCF
Percent gas recovery to date	individual reservoirs not determined	96%	65%
Recovery MCF/ac-ft (field to date)	individual reservoirs not determined	~502 MCF/ac-ft	~211 MCF/ac-ft

[a]Compressibility factor (Z) estimated from standard reservoir engineering chart using T_{res} and P_{res} values listed in this table. T_{res} is in °Rankine (add 460° to reservoir temperature that is measured in °F), P_{res} = reservoir pressure.

[b]B_g calculated using the formula: $B_g = \frac{35.4 \times P_{res}}{T_{res} \times Z}$. The Z factor is stated above.

[c]Original gas in-place (OGIP) determined from the following formula: Reserves (MCF) = 43.56 × Area (acres) × Sand thickness (ft) × Porosity (%) × (1-S_w) × B_g.

more gas than any of the other reservoirs represented on the graph. For a drop of 1,000 PSI (from 2000 to 1000 PSI), it produced 1,800 MMCFG. Any of the other three wells produced no more than 700 MMCFG with the same pressure decline.

The next curve from the top (designated by squares) represents gas production from the upper Jefferson sandstone in the Hall-Jones 1-Woods well in Area 3. The Jefferson is 21 net ft thick in that well, but the lower 6 ft are wet. The shape and slope of the curve indicates that the Woods well cannot produce as much gas per PSI drawdown as the Bartleson well. Both the pay sand thickness and extent are less in the Woods well, so the difference appears related more to the size of the reservoir than to differences in reservoir quality.

The third curve (designated with Xs) represents gas production from the lower Jefferson sandstone in the National Oil 1-14 Fisher well in Area 1. In that well the reservoir is only 6 ft thick and is laterally discontinuous except to the south. The shape and slope of the curve indicates a limited reservoir. The pressure decline of 1,000 PSI (2,000–1,000 PSI) produced <500 MMCFG.

The lowest curve (designated by diamonds) represents gas production from the Cromwell Sandstone in the Gose

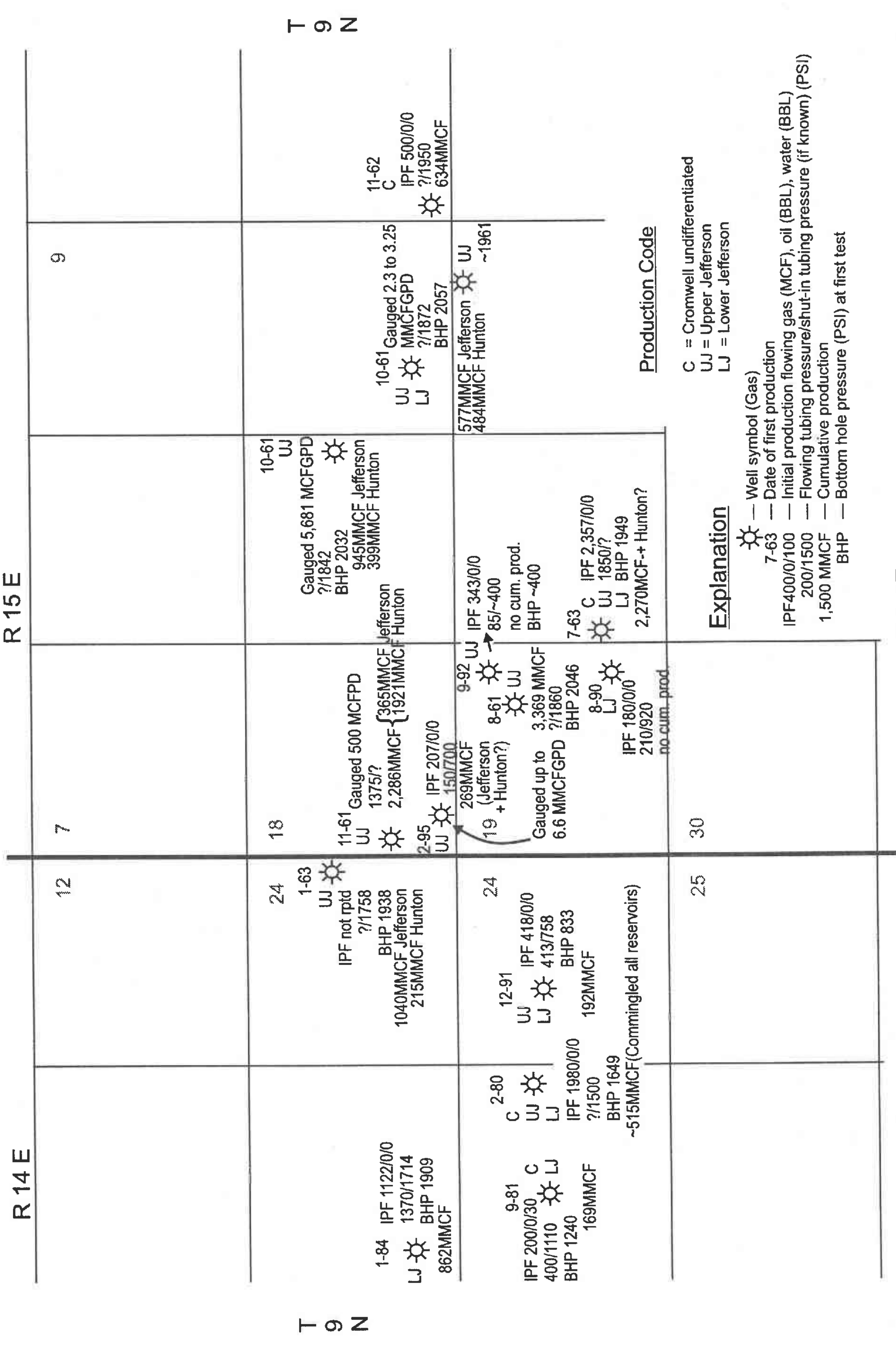
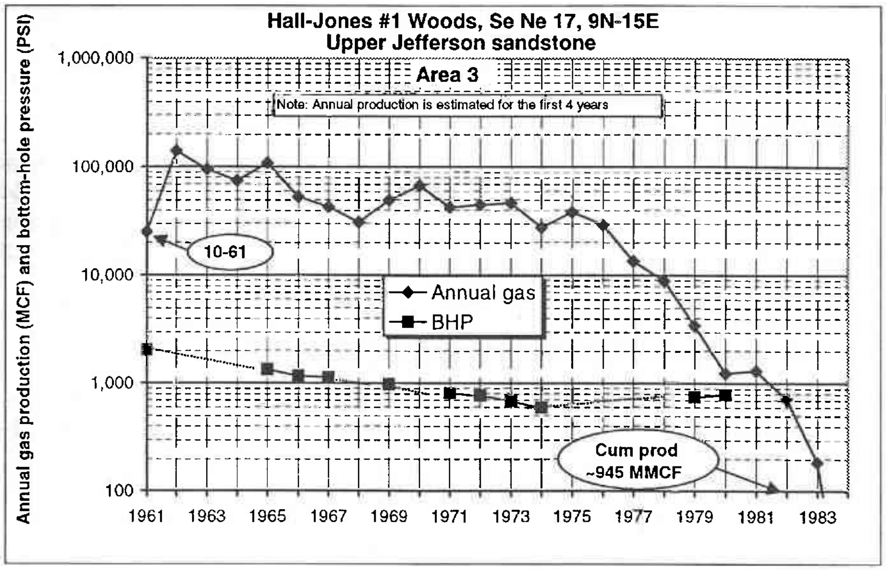


Figure 55. Reservoir information map of Raiford SE Field showing producing reservoir, date of first production, initial production (IP), flowing and shut-in tubing pressure (FTP, SITP), and cumulative production through June 2002.



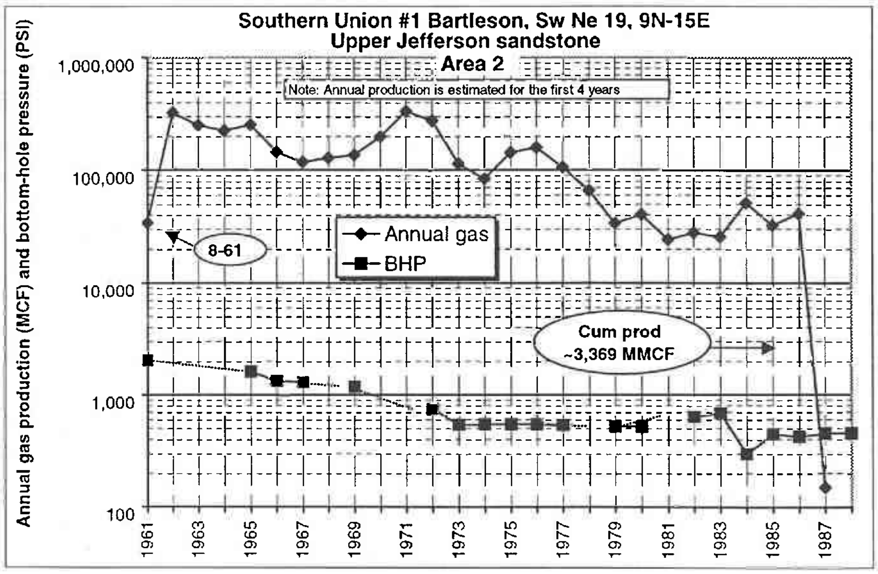


Figure 56. Production- and pressure-decline curves for two wells producing from the upper Jefferson sandstone in Raiford SE Field through June 2002.

& Man 1-Turley well in Area 3. The steep curve also indicates that this reservoir is of limited areal extent.

DRILLING AND COMPLETION PRACTICES

Wells in Raiford SE Field vary in depth from 4,200 to 5,800 ft. They are drilled using traditional water-based drilling fluids to at least 4,700–4,900 ft in order to fully penetrate the Jefferson sandstone. Operators generally set 8⅝-in. surface casing to 400–600 ft, then set either 4½- or 5½-in. intermediate casing to TD. Some newer wells also set 2⅞-in. production tubing and 10¾-in. surface casing. Completion reports indicate that many wells are acidized with 500–2,500 gallons of 7.5% HCl. All Cromwell completions are stimulated with a fracture treatment consisting of 15,000–25,000 gallons of water plus 12,000–25,000 pounds of sand. More recent protocols incorporate nitrogen foam to reduce formation damage caused by water sensitive clays. Foam treatments probably are about the same as those used in Scipio; 600,000–900,000 standard cubic ft of nitrogen foam plus 40,000 pounds of sand. Dry-hole costs are estimated to be $84,000 for a conventional vertical well drilled to a depth of 4,700 ft. The cost of a well completed in a single zone including drilling, completion, and stimulation is about $179,000. These are estimates typical for small operators who usually contract with more competitive service companies. Wells usually take from 2 to 5 weeks to drill.

ACKNOWLEDGMENTS

Completion of this study was accomplished largely through the efforts of many people, including the Oklahoma Geological Survey as a whole. Special recognition is given Dr. Charles Mankin, director of the Survey, for providing persistent support of this project.

Several companies and consulting geologists contributed greatly to this project by providing technical information, field and well-log data, core data, and geological interpretations. Most important are the contributions

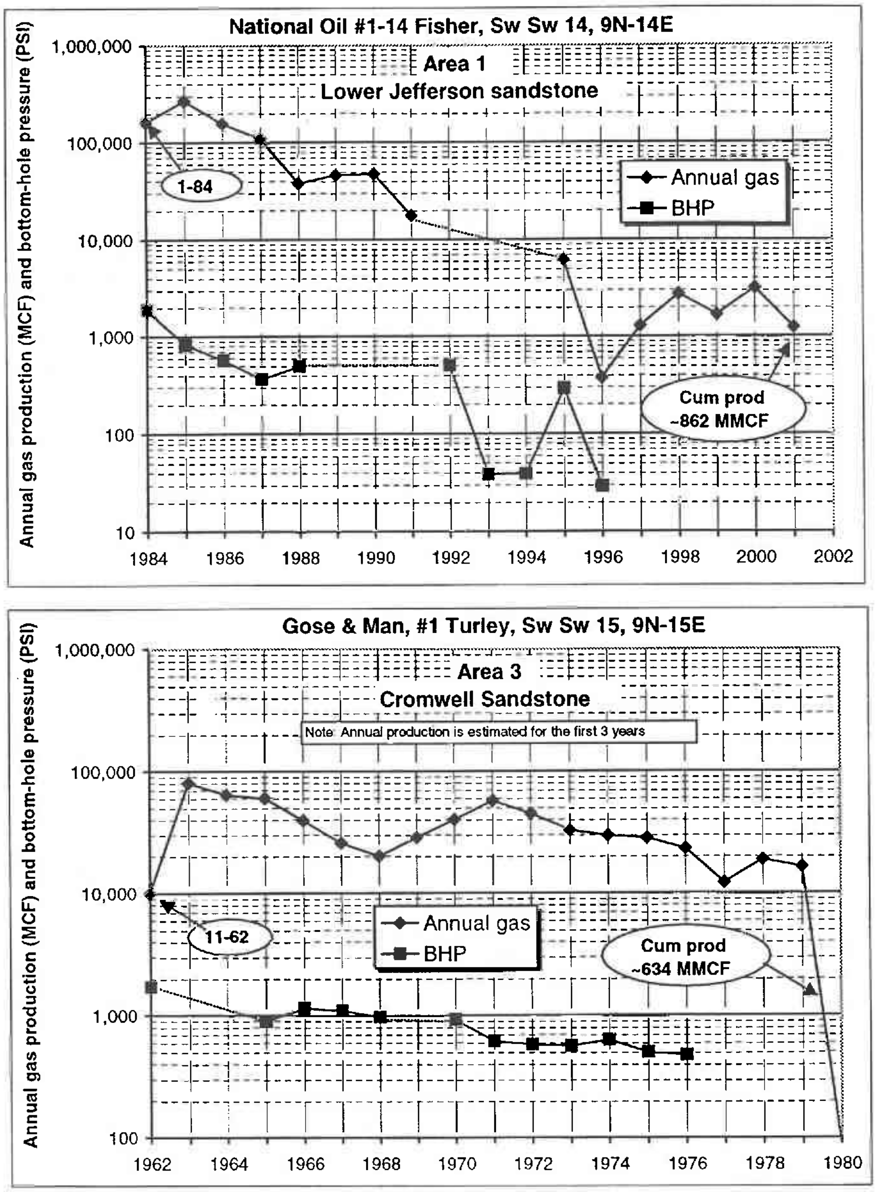


Figure 57. Production- and pressure-decline curves for two wells producing from the Cromwell Sandstone and lower Jefferson sandstone in Raiford SE Field through June 2002.

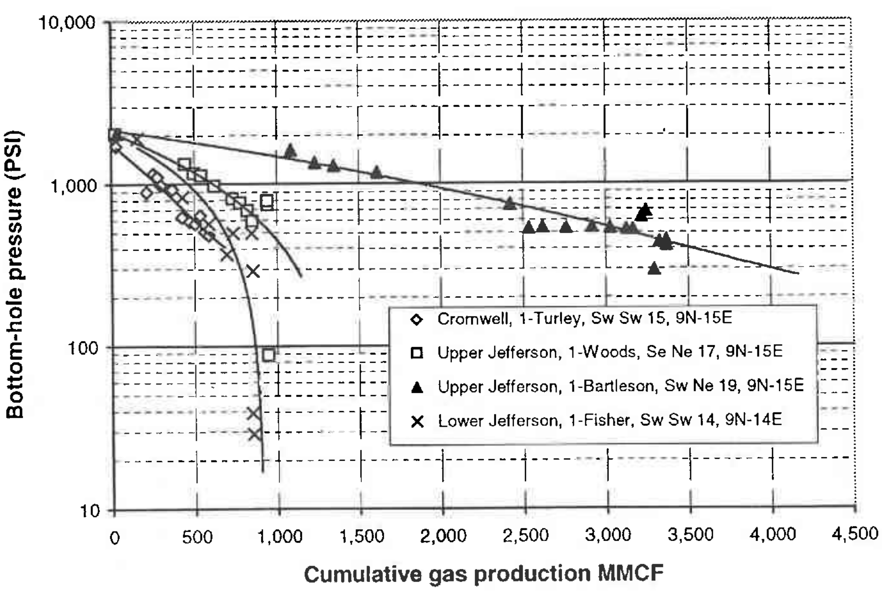


Figure 58. Graph showing relationship between pressure and cumulative gas production for four wells producing from the upper and lower Jefferson sandstone and Cromwell Sandstone in Raiford SE Field.

TABLE 8. — Annual Production and Pressure Data Attributable Primarily to One Zone for Four Wells in Raiford SE Field

	Lower Jefferson *First production 1-84* National Oil (Midcontinent O&G) 1-14 Fisher Ne Sw Sw 14, 9N-14E			Upper Jefferson *First production 8-61* Southern Union (XAE Corp.) 1 Bartleson Sw Ne 19, 9N-15E			Upper Jefferson *First production 10-61* Hall-Jones (Edwards & Leach) 1-Woods Se Ne 17, 9N-15E			Cromwell *First production 11-62* Gose & Man (Getty Oil) 1 Turley Sw Sw 15, 9N-15E		
Date	Annual Gas MCF)	Cum prod (MCF)	Bottom-hole Pressure	Annual Gas MCF)	Cum prod (MCF)	Bottom-hole Pressure	Annual Gas MCF)	Cum prod (MCF)	Bottom-hole Pressure	Annual Gas MCF)	Cum prod (MCF)	Bottom-hole Pressure
1961				Production 1961 through 1964		2,046	Production 1961 through 1964		2,032			
1962										Production 1962 through 1964		1,715
1963												
1964				833,977	833,977		335,041	335,041		154,181	154,181	
1965				252,676	1,086,653	1,605	108,652	443,693	1,333	60,274	214,455	895
1966				146,262	1,232,915	1,346	52,989	496,682	1,169	39,515	253,970	1,157
1967				117,465	1,350,380	1,293	42,876	539,558	1,130	25,742	279,712	1,107
1968				127,925	1,478,305		30,775	570,333		20,143	299,855	982
1969				136,296	1,614,601	1,177	49,586	619,919	972	28,691	328,546	
1970				196,841	1,811,442		67,517	687,436		40,081	368,627	928
1971				334,075	2,145,517		42,361	729,797	812	57,137	425,764	623
1972				274,445	2,419,962	745	44,731	774,528	765	45,124	470,888	586
1973				114,113	2,534,075	535	46,509	821,037	688	33,095	503,983	569
1974				83,496	2,617,571	543	27,533	848,570	590	29,942	533,925	640
1975				142,789	2,760,360	540	38,315	886,885		28,687	562,612	505
1976				159,095	2,919,455	540	29,214	916,099		23,424	586,036	481
1977				106,668	3,026,123	534	13,419	929,518		12,325	598,361	
1978				66,372	3,092,495		8,884	938,402		18,962	617,323	
1979				33,840	3,126,335	523	3,447	941,849	751	16,604	633,927	
1980				40,454	3,166,789	523	1,246	943,095	793	87	634,014	
1981				24,267	3,191,056		1,312	944,407				
1982				27,889	3,218,945	633	717	945,124				
1983				25,512	3,244,457	682	186	945,310	88			
1984	161,419	161,419	1,909	51,226	3,295,683	296	4	945,314				
1985	268,172	429,591	829	32,419	3,328,102	442						
1986	155,890	585,481	566	40,973	3,369,075	420						
1987	109,119	694,600	367	150	3,369,225	451						
1988	38,546	733,146	496			451						
1989	46,613	779,759										
1990	47,964	827,723										
1991	17,982	845,705										
1992		845,705	496									
1993		845,705	39									
1994		845,705	39									
1995	6,271	851,976	292									
1996	374	852,350	29									
1997	1,288	853,638										
1998	2,737	856,375										
1999	1,692	858,067										
2000	3,159	861,226										
2001	1,240	862,466										
2002												
Cumulative Production	**862,466 MCF**			**3,369,225 MCF**			**945,314 MCF**			**634,014 MCF**		

Data from IHS Energy, current through June 2002.

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Appendixes

Appendix 1

Oil and Gas Production Data for Fields Having Production in Part or Fully from the Cromwell, Jefferson, or Wapanucka Reservoirs

Map		Location					Activity	*NRIS* production[1] 1979 - 10/2001			International Oil Scouts[2] Production from discovery through 1999[1]	
Code	Original District, Trend,		Township		Range		Discovery			Dominant		
Pl. 7	or Field Name	County	#	Direction	#	Direction	Date	Oil (Bbls)	Gas (MCF)	Phase	Oil (Bbls)	Gas (MCF)
1	ADAMS DISTRICT	HUGHES	8	N	9	E	4/8/1937	300,535	4,173,567	O&G	3,598,749	28,619,361
2	ALABAMA	HUGHES	9	N	11	E	1917	1,067,014	1,831,398	OIL	2,752,901	6,853,292
3	ALABAMA E	HUGHES	9	N	11	E	9/3/1947		203,545	GAS	30,811	582,307
4	ALABAMA SE	HUGHES	9	N	11	E	4/27/1941			GAS	1,180,251	0
5	ALABAMA S	HUGHES	9	N	11	E	6/3/1959	19,648	2,486,828	GAS	21,539	2,084,263
6	ALABAMA SW	HUGHES	9	N	11	E	9/1/1948	26,098		OIL	1,159,842	227,660
7	ALLEN DISTRICT	PONTOTOC	5	N	7	E	1913	28,275,742	7,371,549	OIL	10,507,743	0
8	ASHLAND	PITTSBURG	4	N	12	E	1/3/1976	62	98,749,491	GAS	0	40,648,772
9	ASHLAND N	PITTSBURG	4	N	12	E	8/17/1967	3,569	6,855,516	GAS	0	5,943,794
10	ASHLAND S	PITTSBURG	3	N	11	E	11/7/1938		57,873,432	GAS	0	134,488,949
11	ATWOOD E	HUGHES	5	N	9	E	8/29/1966	168,056	92,909	OIL	357,774	25,551
12	ATWOOD N	HUGHES	6	N	9	E	9/13/1949	847,156	2,737,819	OIL	491,597	2,705,190
13	ATWOOD SE	HUGHES	5	N	10	E	2/17/1966	4,819	1,827,300	GAS	16,384	2,049,029
14	BALD HILL	OKMULGEE	14	N	14	E	1908	4,795,876	8,537,203	OIL	14,675,463	19,188,522
15	BEARDEN	OKFUSKEE	10	N	9	E	1924	18,585	5,139,785	GAS	31,861	51,142,826
16	BEARDEN E	OKFUSKEE	10	N	9	E	11/30/1948	280	21,147	GAS	24,310	3,402,733
17	BEARDEN NE	OKFUSKEE	10	N	9	E	11/30/1946	10,232	160,339	O&G	21,183	557,706
18	BEARDEN NW	OKFUSKEE	10	N	8	E	1942	162,866	1,301,626	O&G	4,095,160	6,388,463
19	BEGGS DISTRICT	OKMULGEE	15	N	12	E	1958	1,992,792	4,810,278	OIL	10,303,482	26,008,520
20	BENJAMIN	HUGHES	8	N	8	E	1949	364,133	333,522	OIL	3,326,449	2,356,683
21	BETHEL	SEMINOLE	9	N	7	E	1924	444,016	4,286,726	O&G	7,385,245	10,949,221
22	BETHEL E	SEMINOLE	9	N	8	E	1941	194,500	1,446,459	O&G	207,398	3,638,390
23	BETHEL NE	SEMINOLE	10	N	7	E	1941	79,176	545,581	O&G	653,738	329,329
24	BETHEL N	SEMINOLE	10	N	7	E	1937	80,324	1,842,471	GAS	6,016,004	3,476,448
25	BLAKELY	OKFUSKEE	11	N	10	E	Mar-56	70,779	534,784	O&G	1,081,158	1,283,208
26	BLAKELY N	OKFUSKEE	12	N	10	E	8/21/1922		134,622	GAS	141,012	2,315,756
27	BLAKELY SE	OKFUSKEE	11	N	11	E	7/18/1949	22,006	57,479	OIL	6,923	128,736
28	BOLEY S	OKFUSKEE	12	N	8	E	1/4/1980		7,803	GAS	No data	No data
29	BOWLEGS	SEMINOLE	8	N	6	E	1927	4,318,372	2,173,255	OIL	172,239,591	6,539,091
30	BOYNTON	MUSKOGEE	14	N	15	E	1914	1,125,063	436,024	OIL	4,702,996	1,143,891
31	BRENT	SEQUOYAH	10	N	24	E	10/22/1957		759,117	GAS	0	1,132,386
32	BREWER S	PITTSBURG	3	N	14	E	3/26/1962		62,467,351	GAS	0	68,415,530
33	BRINTON	OKMULGEE	13	N	12	E	1915	28,311	1,203,534	GAS	50,603	9,932,650
34	BROOKEN	HASKELL	9	N	18	E	12/5/1925	3,789	245,861,299	GAS	3,526	112,851,632
35	BRYANT E	OKMULGEE	11	N	12	E	9/30/1958		11,764	GAS	13,380	5,226,719
36	BRYANT SE	OKFUSKEE	10	N	12	E	1/22/1916	150	9,087	GAS	300	1,913,134
37	BRYANT S	OKFUSKEE	10	N	12	E	4/12/1976	565	464,819	GAS	71,220	1,935,154
38	CABANISS NW	PITTSBURG	6	N	12	E	10/4/1976		5,338,402	GAS	0	5,104,974
39	CALVIN	HUGHES	6	N	10	E	5/14/1951	103,922	25,583	OIL	542,902	149,237
40	CALVIN E	HUGHES	6	N	10	E	11/5/1982	14,992	1,285,716	GAS	673	974,193
41	CALVIN N	HUGHES	6	N	10	E	12/8/1987			GAS	197,664	847,365
42	CALVIN NW	HUGHES	6	N	10	E	6/9/1966	353,533	5,061,045	O&G	346,016	1,220,158
43	CALVIN SE	HUGHES	5	N	10	E	8/23/1962		13,182,841	GAS	0	2,640,410
44	CALVIN S	HUGHES	5	N	10	E	3/23/1938	313,483	1,883,136	O&G	841,355	7,994,667
45	CALVIN W	HUGHES	6	N	10	E	3/1/1973	123	68,664	GAS	1,735	884,677
46	CANADIAN	PITTSBURG	8	N	16	E	5/24/1978	1,470	33,974,329	GAS	2,327,605	46,863,085
47	CARSON	HUGHES	8	N	11	E	2/26/1952	541	3,981,440	GAS	90,731	29,408,250
48	CARSON W	HUGHES	8	N	11	E	11/14/1954		2,019,981	GAS	431	2,771,488
49	CASTLE	OKFUSKEE	11	N	9	E	3/2/1960	13,863	47,748	OIL	3,667	362,003
50	CASTLE E	OKFUSKEE	12	N	9	E	3/14/1944	147,702	114,711	OIL	3,733,323	1,006,566
51	CASTLE SW	OKFUSKEE	11	N	8	E	4/24/1941	86,312	13,072	OIL	1,504,942	294,051
52	CEDARS	LEFLORE	9	N	27	E	5/18/1946		54,936,891	GAS	0	58,911,190
53	CENTRAHOMA	COAL	1	N	10	E	1937	872,984	27,611,986	GAS	4,146,372	121,662,468
54	CHECOTAH	MCINTOSH	11	N	17	E	3/11/1977		1,417,610	GAS	2,123	4,891,438
55	CHILES DOME	COAL	3	N	9	E	1943	134,473	4,970,842	GAS	124,341	28,341,920
56	CHIMNEY MOUNTAIN	SEMINOLE	10	N	7	E	8/25/1948	136,311		OIL	161	298,992
57	CITRA NE	HUGHES	4	N	9	E	3/10/1963	69,237		OIL	1,094,064	No data
58	CLEARVIEW DISTRICT	OKFUSKEE	11	N	10	E	1957	766,852	1,922,815	OIL	2,288,213	15,890,843
59	COALGATE NE	COAL	1	N	11	E	5/1/1978		688,403	GAS	0	297,834
60	COALTON	MCINTOSH	11	N	13	E	1907	245,994	11,053,090	GAS	622,457	56,483,613
61	COALTON N	OKMULGEE	12	N	13	E	1953	124,127	635,487	O&G	822,624	2,677,258
62	COLE DISTRICT	MUSKOGEE	14	N	15	E	1958	436,760	1,260,716	OIL	10,969	1,501,036
63	COUNCIL HILL DISTRICT	MUSKOGEE	13	N	15	E	1958	443,820	1,520,925	OIL	2,787,184	4,257,707
64	CROMWELL	SEMINOLE	10	N	8	E	1922	2,890,036	2,303,560	OIL	91,970,514	5,683,581
65	CROMWELL E	OKFUSKEE	10	N	8	E	1940	417,294	42,490	OIL	9,860,475	42,490
66	CROMWELL S	SEMINOLE	9	N	8	E	6/14/1955	944,308	1,635,945	OIL	4,425,529	4,406,114
67	CUMMINGS	MCINTOSH	9	N	14	E	6/23/1936		1,785,762	GAS	0	1,977,957
68	DEANER N	OKFUSKEE	11	N	11	E	12/27/1949	3,128	241,054	GAS	457,244	263,101
69	DEWAR	OKMULGEE	11	N	13	E	8/26/1926			GAS	No data	No data
70	DILL	OKFUSKEE	11	N	8	E	1935	642,812	43,105	OIL	0	0
71	DILL NE	OKFUSKEE	12	N	8	E	7/11/1943	174,513	116,740	OIL	0	0
72	DILL S	SEMINOLE	11	N	8	E	1941	16,048	54,518	OIL	0	0
73	DUSTIN	HUGHES	9	N	12	E	1918	119,114	8,446,933	GAS	73,592	14,843,415
74	DUSTIN NE	OKFUSKEE	10	N	12	E	5/25/1924		28,531	GAS	1,209	789,037
75	DUSTIN SE	HUGHES	9	N	12	E	8/30/1949		273,056	GAS	0	2,565,373
76	DUSTIN W	HUGHES	9	N	11	E	9/1/1960	113,378	804,603	O&G	738,607	1,041,682
77	EARLSBORO	SEMINOLE	9	N	5	E	1927	5,526,306	590,202	OIL	208,370,327	1,186,809

Map Code Pl. 7	Original District, Trend, or Field Name	Location: County	Township #	Township Direction	Range #	Range Direction	Activity: Discovery Date	*NRIS* production[1] 1979 - 10/2001: Oil (Bbls)	Gas (MCF)	Dominant Phase	International Oil Scouts[2] Production from discovery through 1999[1]: Oil (Bbls)	Gas (MCF)
78	EDNA DISTRICT	CREEK	14	N	10	E	1958	574,216	459,174	OIL	1,246,052	1,215,617
79	FISH E	HUGHES	7	N	8	E	9/2/1947	49,741	4,150	OIL	146,699	254,991
80	FITTS	PONTOTOC	2	N	7	E	1933	59,737,847	13,074,045	OIL	223,089,598	53,458,320
81	FITTS W	PONTOTOC	2	N	6	E	6/28/1937	394,949		OIL	2,249,210	No data
82	FUHRMAN	HUGHES	9	N	9	E	1925	101,551	719,369	O&G	2,117,083	580,833
83	FUHRMAN SE	HUGHES	9	N	9	E	5/4/1965		218,357	GAS	0	98,460
84	GANS SE	SEQUOYAH	10	N	25	E	3/2/1990		43,805	GAS	0	46,410
85	GANS SW	SEQUOYAH	10	N	24	E	12/23/1942		2,735,370	GAS	0	5,284,980
86	GARCREEK	SEMINOLE	10	N	7	E	7/28/1946	153,791	38,015	OIL	2,174,466	48,295
87	GARDEN GROVE S	OKFUSKEE	11	N	7	E	7/20/1970	344,410	31,875	OIL	6,259	No data
88	GERTY E	HUGHES	4	N	10	E	7/15/1982	2,533	205,685	GAS	177,472	3,680,709
89	GERTY NW	HUGHES	5	N	9	E	9/1/1954	728,571	10,402,064	O&G	869,152	12,293,238
90	GERTY W	HUGHES	4	N	9	E	4/8/1955			OIL	2,966	90,610
91	GILCREASE	HUGHES	9	N	9	E	Mar-47	25,545	402,787	O&G	447,366	1,585,006
92	GILCREASE DISTRICT	HUGHES	9	N	9	E	1946	189,074	5,277,917	GAS	378,626	1,701,331
93	GILCREASE SW	HUGHES	9	N	8	E	1946	8,366	589,997	GAS	177,197	919,051
94	GREASY CREEK	HUGHES	8	N	10	E	3/21/1917	1,281,646	49,262,920	GAS	5,765,113	252,837,731
95	GREGORY	OKFUSKEE	10	N	11	E	1934	310,303	4,087,210	O&G	779,625	13,262,785
96	HAMILTON SWITCH	OKMULGEE	14	N	13	E	1909	785,270	3,182,950	OIL	577,561	10,302,663
97	HANNA	MCINTOSH	8	N	13	E	11/3/1978			GAS	320	7,403,011
98	HASKELL	MUSKOGEE	15	N	14	E	1919	588,898	1,312,359	OIL	6,836,743	4,152,970
99	HAYDENVILLE DISTRICT	OKFUSKEE	13	N	9	E	12/7/1938	407,272	350,513	OIL	4,090,076	1,301,251
100	HENRYETTA DISTRICT	OKMULGEE	11	N	12	E	1957	1,176,509	8,659,361	O&G	3,465,628	28,852,212
101	HENRYETTA SE	OKMULGEE	11	N	13	E	3/1/1962			GAS	7,690	1,310,139
102	HENRYETTA S	OKMULGEE	11	N	12	E	10/16/1958		242,672	GAS	5,746	2,731,421
103	HICKORY RIDGE SW	OKFUSKEE	10	N	10	E	4/30/1962	80	1,043	O&G	80,611	2,127,898
104	HILL TOP	HUGHES	5	N	11	E	3/2/1941		1,840,520	GAS	69	18,066,323
105	HILL TOP N	HUGHES	6	N	11	E	5/27/1949		2,520,426	GAS	303	1,976,792
106	HITCHITA NE	MCINTOSH	12	N	15	E	4/27/1973		9,689,335	GAS	0	8,546,692
107	HOFFMAN	OKMULGEE	12	N	13	E	1917	66,695	2,695,081	GAS	95,117	17,133,000
108	HOFFMAN DISTRICT NW	OKMULGEE	12	N	13	E	1953	38,746	1,164,656	GAS	192,554	3,450,257
109	HOFFMAN W	OKMULGEE	12	N	13	E	1953		480,758	GAS	0	1,689,228
110	HOLDENVILLE	HUGHES	7	N	8	E	1946	5,360,229	5,172,852	OIL	100,009,171	36,994,121
111	HOLDENVILLE NE	HUGHES	8	N	9	E	5/4/1955	985,384	5,378,493	O&G	1,034,003	7,211,224
112	HOLDENVILLE N	HUGHES	8	N	9	E	Apr-53	92,552	14,421	OIL	176,825	270,614
113	HOLDENVILLE SE	HUGHES	7	N	9	E	5/26/1952	393,178		OIL	146,141	0
114	HORNS CORNER	HUGHES	6	N	10	E	6/8/1943	753,496	5,220,068	O&G	3,801,529	18,201,271
115	HORNS CORNER N	HUGHES	7	N	10	E	3/9/1944	290,854	880,416	OIL	1,144,972	4,452,609
116	HORNTOWN SE	HUGHES	7	N	10	E	3/10/1955		12,578,566	GAS	6,765	9,249,010
117	IRON POST	CREEK	14	N	8	E	1917	3,850,972	3,560,237	OIL	25,117,105	12,000,322
118	IRON POST DISTRICT SE	CREEK	14	N	9	E	8/27/1953	353,290	245,649	OIL	365,593	298,534
119	JEFFERSON N	HUGHES	8	N	8	E	11/19/1946	118,538	119,445	OIL	315,557	493,834
120	JESSE E	COAL	1	N	8	E	12/16/1969	10,413		OIL	No data	No data
121	KEATON	OKFUSKEE	12	N	10	E	1931	19,400	341,353	O&G	115,666	2,177,170
122	KEATON W	OKFUSKEE	12	N	10	E	4/14/1960			GAS	188,665	418,676
123	KEOKUK	SEMINOLE	10	N	6	E	1933	2,156,404	2,184,681	OIL	15,260,084	9,738,658
124	KEOTA	HASKELL	9	N	23	E	2/23/1979		17,057,024	GAS	0	15,221,702
125	KINTA	HASKELL	8	N	22	E	1962	298	1,345,667,482	GAS	No data	No data
126	KIOWA	PITTSBURG	3	N	13	E	6/25/1976		1,059,599	GAS	0	5,022,301
127	KIOWA NW	PITTSBURG	3	N	12	E	5/23/1975	554	19,843,978	GAS	745	19,557,066
128	KONAWA-DORA	SEMINOLE	6	N	5	E	1962	5,177,710	817,242	OIL	21,112,423	0
129	KREBS SE	PITTSBURG	5	N	15	E	11/25/1991		66,971	GAS	0	42,734
130	LAFFOON SE	OKFUSKEE	12	N	7	E	2/13/1936	511,956	3,032,221	O&G	6,971,900	17,338,361
131	LAMAR E	HUGHES	7	N	11	E	8/24/1950	61,607	14,469,315	GAS	258,186	16,694,079
132	LENNA W	MCINTOSH	11	N	14	E	12/10/1996		280,761	GAS	0	552,920
133	LITTLE RIVER	SEMINOLE	7	N	6	E	1927	4,709,528	3,268,966	OIL	142,960,681	19,315,164
134	LITTLE RIVER E	SEMINOLE	7	N	7	E	10/9/1928	1,036,779	381,924	OIL	26,055,989	2,738,003
135	LONG	HUGHES	8	N	9	E	11/23/1926	61,283	3,511,938	GAS	399,240	5,198,389
136	LONG N	HUGHES	8	N	9	E	9/7/1949		975,563	GAS	241	931,148
137	LULA E	COAL	3	N	9	E	12/11/1957	98,720	171,406	OIL	665,123	118,986
138	LULA NE	COAL	3	N	9	E	5/22/1943	73,076	2,316,306	GAS	3,381	12,561,383
139	LULA SE	COAL	3	N	9	E	8/6/1975	15,278		OIL	80,136	150,584
140	LULA S	COAL	2	N	8	E	12/30/1957	72,276		OIL	281,058	161,153
141	LYONS-QUINN	OKFUSKEE	10	N	11	E	1921	1,086,746	7,625,694	O&G	5,434,889	50,910,434
142	MASON	OKFUSKEE	12	N	9	E	7/25/1940	32,001		OIL	669,590	801,415
143	MCALESTER	PITTSBURG	5	N	14	E	10/10/1965		234,391	GAS	0	3,352,895
144	MICAWBER SE	OKFUSKEE	13	N	8	E	10/21/1925	367		OIL	461,904	57,788
145	MICAWBER S	OKFUSKEE	13	N	8	E	5/20/1966		15,869	GAS	7,809	173,471
146	MIDWEST	OKFUSKEE	11	N	9	E	3/31/1941	31,324	2,697,602	GAS	315,052	18,346,945
147	MISSION	SEMINOLE	8	N	5	E	1928	1,201,982	123,186	OIL	28,486,467	0
148	MORGAN	OKFUSKEE	12	N	11	E	1920	135,666	404,949	OIL	1,200,338	2,038,323
149	MORRIS DISTRICT	OKMULGEE	13	N	14	E	1958	1,360,576	7,767,218	O&G	4,340,071	21,640,383
150	MORSE DISTRIC	OKFUSKEE	12	N	9	E	7/22/1924	428,265	458,818	OIL	2,920,351	3,144,590
151	MORSE SE	OKFUSKEE	12	N	10	E	12/30/1953	27,567	116,171	OIL	250,106	386,451
152	MORSE S	OKFUSKEE	12	N	10	E	9/26/1957			OIL	134,522	222,785
153	MOUNDS DISTRICT	CREEK	15	N	12	E	1958	1,620,595	4,004,012	OIL	0	1,366,256
154	NUYAKA DISTRICT	OKMULGEE	14	N	11	E	1958	273,942	966,820	OIL	1,943,770	2,489,408
155	OAKMAN DISTRICT	PONTOTOC	4	N	5	E	1988	1,909,825	2,078,479	OIL	1,233,413	9,246,838
156	OKEMAH	OKFUSKEE	10	N	9	E	1921	337,698	8,366,889	GAS	2,294,731	21,486,878
157	OKEMAH E	OKFUSKEE	11	N	10	E	1940	126,601	260,818	OIL	879,998	332,486
158	OKEMAH N	OKFUSKEE	11	N	9	E	2/4/1941	976,117	2,073,714	OIL	6,426,343	12,588,073
159	OKEMAH NW	OKFUSKEE	12	N	9	E	4/15/1940			GAS	32,618	2,961,813
160	OKEMAH W	OKFUSKEE	11	N	9	E	1941	22,182	375,766	O&G	112,824	8,351,782
161	OKFUSKEE DISTRICT	OKFUSKEE	13	N	10	E	1958	29,757	123,392	OIL	297,733	401,119

Map Code Pl. 7	Original District, Trend, or Field Name	Location: County	Township #	Township Direction	Range #	Range Direction	Activity: Discovery Date	*NRIS* production[1] 1979 - 10/2001: Oil (Bbls)	*NRIS* production[1] 1979 - 10/2001: Gas (MCF)	Dominant Phase	International Oil Scouts[2] Production from discovery through 1999[1]: Oil (Bbls)	International Oil Scouts[2] Production from discovery through 1999[1]: Gas (MCF)
162	OKMULGEE DISTRICT	OKMULGEE	13	N	13	E	1941	607,249	3,115,367	O&G	4,692,839	12,901,838
163	OKTAHA NW	MUSKOGEE	13	N	17	E	3/17/1943	20,424	72,574	OIL	57,715	1,468,924
164	OLYMPIC	OKFUSKEE	9	N	8	E	1935	1,073,933	5,949,214	O&G	33,329,865	10,383,598
165	OLYMPIC SW	HUGHES	9	N	8	E	5/6/1954			GAS	9,512	242,529
166	OWL	COAL	1	N	9	E	10/8/1983	32,268	315,930	O&G	1,933	121,396
167	PAPOOSE	HUGHES	9	N	9	E	1923	306,718	1,161,068	OIL	27,850,594	2,132,981
168	PAPOOSE SE	HUGHES	9	N	9	E	1/11/1946	11,557	97,372	O&G	129	1,994,436
169	PENO	LEFLORE	10	N	27	E	12/3/1965		74,809,509	GAS	0	46,673,862
170	PINE HOLLOW S	PITTSBURG	5	N	13	E	11/27/1959	2,301	70,656,574	GAS	0	135,487,654
171	PITTSBURG	PITTSBURG	2	N	14	E	2/6/1979		74,409,774	GAS	577	66,314,802
172	POLLYANNA	OKMULGEE	16	N	11	E	1921	1,021,239	4,551,898	OIL	3,824,968	12,737,055
173	PORUM S	MUSKOGEE	10	N	19	E	1/5/1978		17,369	GAS	0	55,184
174	QUINTON DISTRICT	PITTSBURG	7	N	18	E	15-Sep		55,552,090	GAS	1,179	144,478,699
175	RAIFORD N	MCINTOSH	10	N	15	E	10/2/1973		2,281,339	GAS	0	3,051,575
176	RAIFORD SE	MCINTOSH	9	N	14	E	2/14/1956		4,694,947	GAS	0	4,229,124
177	REAMS NW	PITTSBURG	7	N	14	E	9/5/1963	576	50,580,254	GAS	0	38,749,709
178	REAMS SE	PITTSBURG	6	N	15	E	2/23/1943		16,658,881	GAS	0	27,794,412
179	RENTIESVILLE	MCINTOSH	12	N	17	E	9/21/1978			GAS	0	488,907
180	ROSENWALD	OKFUSKEE	13	N	8	E	12/10/1948	1,974		OIL	1,448,128	1,268,625
181	RUSK	OKFUSKEE	11	N	8	E	10/19/1949	2,357		OIL	2,186,641	0
182	SALEM	MCINTOSH	10	N	13	E	1/19/1960		140,388	GAS	0	358,230
183	SALEM N	OKMULGEE	11	N	13	E	5/27/1965			GAS	0	664,048
184	SALEM SE	MCINTOSH	10	N	14	E	8/13/1964		2,027,889	GAS	0	8,090,508
185	SALEM SW	MCINTOSH	10	N	13	E	9/4/1957	86	906,420	GAS	9,185	5,749,428
186	SCHULTER	OKMULGEE	12	N	13	E	1907	111,422	1,092,754	O&G	1,187,864	9,083,784
187	SCIPIO NW	PITTSBURG	8	N	13	E	2/7/1948		29,582,701	GAS	0	35,539,803
188	SCOTT GAS AREA	OKFUSKEE	10	N	10	E	1961	6,219	3,221,865	GAS	32,272	13,339,785
189	SEARIGHT	SEMINOLE	9	N	6	E	1926	6,699,049	1,180,449	OIL	67,306,326	4,398,491
190	SEARIGHT E	SEMINOLE	10	N	6	E	1939	33,935	267,440	O&G	601,308	314,395
191	SEARIGHT NE	SEMINOLE	10	N	6	E	9/11/1973	694,991	1,506,350	OIL	200,090	221,586
192	SEARIGHT N	SEMINOLE	10	N	6	E	1934	755,812	378,204	OIL	8,034,775	1,388,002
193	SEMINOLE	SEMINOLE	8	N	6	E	1923	8,795,116	3,991,078	OIL	285,966,985	12,042,672
194	SHADY GROVE W	HUGHES	6	N	11	E	2/15/1963	615,789	4,537,239	O&G	597,649	6,373,062
195	SHELDON	OKFUSKEE	12	N	11	E	1916	81,879	2,022,728	GAS	2,189,043	3,400,054
196	SHORT SE	SEQUOYAH	12	N	27	E	12/12/1996		1,619,390	GAS	0	1,153,931
197	SHORT S	SEQUOYAH	12	N	26	E	12/6/1995		1,540,084	GAS	0	1,112,399
198	SPENCER DISTRICT	TULSA	16	N	14	E	1950	379,724	1,531,625	OIL	1,746,349	4,276,960
199	SPIRO SE	LEFLORE	9	N	25	E	12/19/1962		6,428,967	GAS	0	14,181,763
200	STIDHAM E	MCINTOSH	10	N	16	E	4/11/1975		342,750	GAS	0	327,963
201	STIDHAM S	MCINTOSH	10	N	15	E	5/9/1977	66	6,112,559	GAS	879	2,029,938
202	STIGLER	HASKELL	9	N	21	E	2/1/1974		12,372,718	GAS	0	17,444,115
203	STIGLER W	HASKELL	9	N	20	E	5/28/1976		47,755,664	GAS	0	39,599,780
204	STONEBLUFF DISTRICT	WAGONER	16	N	14	E	1949	1,159,138	368,785	OIL	7,905,473	263,345
205	SYLVIAN	SEMINOLE	10	N	7	E	12/11/1941	273,384	1,194,027	OIL	3,492,986	2,122,302
206	SYLVIAN E	SEMINOLE	10	N	7	E	1949	21,975	12,299	OIL	1,678,921	105,915
207	SYLVIAN N	SEMINOLE	11	N	7	E	9/2/1970	10,161		OIL	No data	No data
208	TIGER FLATS	OKMULGEE	13	N	11	E	1908	948,742	4,493,954	OIL	3,668,976	21,950,308
209	TIGER FLATS SE	OKMULGEE	12	N	12	E	1947	10,247	36,482	OIL	10,561	1,048,858
210	TRANSCO	SEMINOLE	7	N	7	E	Dec-53			OIL	138,172	347,076
211	TUPELO	COAL	2	N	8	E	8/1/1981	234		OIL	No data	No data
212	TUPELO NE	COAL	2	N	9	E	12/21/1961	57,014	314,508	O&G	195,314	1,899,433
213	TUPELO N	COAL	2	N	8	E	10/17/1967			OIL	41,730	5,455
214	TUPELO NW	COAL	2	N	8	E	12/18/1952			OIL	87,909	0
215	TUSKEGEE DISTRICT	CREEK	14	N	10	E	1958	703,563	372,160	OIL	4,596,209	954,909
216	TUSKEGEE W	CREEK	13	N	9	E	1947	294,058	261,544	OIL	791,570	363,663
217	TYROLA NE	SEMINOLE	5	N	6	E	1/4/1938	1,269,129	1,346,517	OIL	4,698,092	3,266,975
218	ULAN E	PITTSBURG	7	N	14	E	4/1/1945		20,158,016	GAS	0	8,868,339
219	VALLEY GROVE	OKFUSKEE	12	N	8	E	11/21/1943			OIL	38,859	10,000
220	VALLEY GROVE S	OKFUSKEE	12	N	8	E	5/6/1947			OIL	165,795	20,713
221	VALLEY GROVE SW	OKFUSKEE	12	N	8	E	5/4/1954	13,608		OIL	187,989	0
222	VERNON N	MCINTOSH	10	N	13	E	7/1/1979		251,028	GAS	0	238,328
223	WELEETKA DISTRICT	OKFUSKEE	10	N	11	E	1957	63,958	802,004	O&G	236,105	8,083,781
224	WELEETKA DISTRICT EAST	OKFUSKEE	10	N	11	E	1947	40,364	1,984,335	GAS	1,131,140	8,241,565
225	WELEETKA SE	OKFUSKEE	10	N	11	E	2/5/1973		133,505	GAS	No data	No data
226	WELEETKA W	OKFUSKEE	10	N	11	E	1940	244,321	33,903	OIL	2,204,989	1,909,887
227	WETUMKA	HUGHES	9	N	10	E	1919	52,569	4,807,793	GAS	2,326,489	9,342,749
228	WETUMKA DISTRICT EAST	HUGHES	9	N	10	E	1946	39,387	3,594,393	GAS	550,414	9,984,769
229	WEWOKA DISTRICT	SEMINOLE	8	N	7	E	1955	3,529,563	7,727,282	OIL	67,551,059	12,873,951
230	WEWOKA DISTRICT	SEMINOLE	8	N	8	E	1945	154,389	340,045	OIL	1,333,321	1,193,424
231	WEWOKA E	SEMINOLE	8	N	8	E	1947	826,189	1,938,900	OIL	3,519,958	4,359,847
232	WEWOKA NE	SEMINOLE	8	N	8	E	1941	134,255	358,619	OIL	3,214,331	4,977,663
233	WHITE ROSE SW	OKFUSKEE	13	N	9	E	4/1/1942	13,009		OIL	228,112	0
234	WILBURTON	LATIMER	5	N	18	E	12/15/1960		1,169,676,863	GAS	661	1,689,450,422
235	WILCOX	OKMULGEE	14	N	11	E	1919	364,029	391,169	OIL	4,303,158	212,775
236	YAHOLA DISTRICT	MUSKOGEE	15	N	15	E	1958	88,930	712,877	O&G	805,437	2,597,174
237	YEAGER	HUGHES	8	N	10	E	2/28/1925	383,532	11,444,261	GAS	3,045,155	21,706,788
238	YOUNGSTOWN	OKMULGEE	13	N	11	E	1915	510,402	844,737	OIL	2,710,225	3,842,319

Note: NRIS field outlines derived from Boyd (2002).

[1] Field production is not formation specific, i.e., it may involve several different reservoirs, not just the Cromwell, Jefferson, or Wapanucka.

[2] Field boundaries probably are not the same as that used by NRIS.

Appendix 2

Various Size Grade Scales in Common Use

(from Blatt and others, 1980, table 3-3)

Udden–Wentworth	ϕ *values*	*German scale†* *(after Atterberg)*	*USDA and Soil Sci. Soc. Amer.*	*U.S. Corps Eng., Dept. Army and Bur. Reclamation‡*
		(Blockwerk)		
Cobbles		—200 mm—	Cobbles	Boulders
			—80 mm—	—10 in.—
—64 mm—	−6			Cobbles
		Gravel (Kies)		—3 in.—
Pebbles				
				Gravel
—4 mm—	−2		Gravel	
				—4 mesh—
Granules				Coarse sand
—2 mm—	−1	—2 mm—	—2 mm—	—10 mesh—
Very coarse sand			Very coarse sand	
—1 mm—	0		—1 mm—	
Coarse sand		Sand	Coarse sand	Medium sand
—0.5 mm—	1		—0.5 mm—	
				—40 mesh—
Medium sand			Medium sand	
—0.25 mm—	2		—0.25 mm—	
Fine sand			Fine sand	Fine sand
—0.125 mm—	3		—0.10 mm—	
Very fine sand			Very fine sand	—200 mesh—
—0.0625 mm—	4	—0.0625 mm—		
			—0.05 mm—	
Silt		Silt		
			Silt	Fines
—0.0039 mm—	8			
		—0.002 mm—	—0.002 mm—	
Clay		Clay (Ton)	Clay	

†Subdivisions of sand sizes omitted.

‡Mesh numbers are for U.S. Standard sieves: 4 mesh = 4.76 mm, 10 mesh = 2.00 mm, 40 mesh = 0.42 mm, 200 mesh = 0.074 mm.

Appendix 3

Abbreviations Used in Text and on Figures, Tables, and Plates

ac-ft	acre-foot
B	barrel(s)
bbl, BBL	barrel(s)
BC	barrels of condensate
BCF	billion cubic (of gas)
BCFG	billion cubic feet of gas
B_g	gas formation volume factor
BHP	bottom-hole pressure
BLW	barrels of load water
BO	barrels of oil
BOPD	barrels of oil per day
BP	bridge plug
BW	barrels of water
BWPD	barrels of water per day
CAL	caliper
CAOF	calculated absolute open flow
CIBP	cast-iron bridge plug
COF	calculated open flow
cum.	cumulative
D&A	dry and abandoned
DF	derrick floor
DST	drillstem test
F	formation factor
FTP	flowing tubing pressure
G	gas
GCM	gas-cut mud
GL	ground level
GOR	gas/oil ratio
GR	gamma ray
HCl	hydrochloric acid
IPF	initial production flowing
IPP	initial production pumping
ISIP	initial shut-in pressure
KB	kelly bushing
MCF	thousand cubic feet (of gas)
MCFG	thousand cubic feet of gas
MCFGPD	thousand cubic feet of gas per day
MMBO	million barrels of oil
MMCF	million cubic feet (of gas)
MMCFG	million cubic feet of gas
MMCFGPD	million cubic feet of gas per day
md	millidarcy(s)
NDE	not deep enough
NL	no log
NPL	no porosity log
NRIS	Natural Resources and Information System (a database)
O&GCM	oil- and gas-cut mud
OGIP	original gas in place
P	pressure (usually reservoir pressure)
P&A	plugged and abandoned
PE	photoelectric (well-logging survey)
por	porosity
ppg	parts per gallon
P_{res}	reservoir pressure
psi, PSI	pounds per square inch
R_t	deep, or true, resistivity
R_w	formation-water resistivity
R_{xo}	resistivity of flushed zone
SITP	shut-in tubing pressure
SP	spontaneous potential
std cu ft	standard cubic feet
SW	salt water
S_w	water saturation
TC	tubing choke
TCF	trillion cubic feet (of gas)
TCFG	trillion cubic feet of gas
TD	total depth
trc	trace
T_{res}	reservoir temperature
W	water
wtr.	water
WP	where productive
WPWA	where productive, well average
Z	compressibility factor
ϕ	porosity

Appendix 4

Glossary of Terms

(as used in this volume)

Definitions modified from Jackson (1997), Sheriff (1991), and Van Wagoner and others (1990).

bioturbation—The churning and stirring of a sediment by organisms.

carbonate—A sediment or sedimentary rock formed by precipitation from aqueous solution of carbonates of calcium, magnesium, or iron; e.g., limestone and dolomite. In referring to rocks, the term "carbonates" also includes those composed of clastic and biogenic grains that are predominantly calcite and/or dolomite in composition.

carbonate ramp—Informally used in this text as a very shallow marine depositional environment in an area between shoreline and deeper parts of a sedimentary basin that is slightly inclined basinward.

channel deposit—An accumulation of clastic material, commonly consisting of sand, gravel, silt, and clay, in a trough or stream channel where the transporting capacity of the stream is insufficient to remove material supplied to it.

detached bar—Informal terminology used to describe a marine sand deposit commonly occurring on the shallow continental shelf that is separated from the mainland (or shoreline) by an expanse of mud (shale). This terminology is used to differentiate from other marine sand deposits that occur adjacent to shorelines, such as distributary-mouth bars.

delta front—A narrow zone where deposition in deltas is most active, consisting of a continuous sheet of sand, and occurring within the effective depth of wave erosion (10 m or less). It is the zone separating the *prodelta* from the *delta plain*, and it may or may not be steep.

delta plain—The level or nearly level surface composing the landward part of a large delta.

diagenesis—All changes that affect sediments after initial deposition, including compaction, cementation, and chemical alteration and dissolution of constituents. It does not include weathering and metamorphism of preexisting sediments.

distributary-mouth bar—The subaqueous (marine) part of the delta composed mostly of sand transported to the delta front by a network of delta plain channels (distributary channels). The distributary mouth bar occurs adjacent to the coastline and therefore is considered "attached."

facies—(a) A mappable, areally restricted part of a lithostratigraphic body, differing in lithology or fossil content from other beds deposited at the same time and in lithologic continuity. (b) A distinctive rock type, broadly corresponding to a certain environment or mode of origin.

fluvial—(a) Of or pertaining to a river or rivers. (b) Produced by the action of a stream or river.

grainstone—A grain-supported carbonate rock that is essentially free of matrix mud or clay.

incised valleys—Entrenched fluvial systems that extend their channels basinward and erode into underlying strata.

isopach—A line drawn on a map through points of equal true thickness of a designated stratigraphic unit or group of stratigraphic units.

millidarcy (md)—The customary unit of measurement of fluid permeability, equivalent to 0.001 darcy.

mudstone—In carbonate rock classification, a mud-supported carbonate rock (carbonate mud) having <10% clastic grains.

offshore bar—A low, elongate sand ridge, built chiefly by wave action, occurring at some distance from, and extending generally parallel with, the shoreline. Syn.: longshore bar.

packstone—A grain-supported carbonate rock containing some matrix mud and fine silt.

permeability—The capacity of a porous rock, sediment, or soil for transmitting a fluid; it is a measure of the relative ease of fluid flow under unequal pressure. The customary unit of measure is the *millidarcy*.

porosity—The ratio of the aggregate volume of interstices in a rock or soil to its total volume. It is usually stated as a percentage.

prodelta—The part of a delta that is below the effective depth of wave erosion, lying beyond the *delta front*, and sloping gently down to the floor of the basin into which the delta is advancing and where clastic river sediment ceases to be a significant part of the basin-floor deposits. Consists entirely, or almost entirely, of clay and silt that became predominantly shale upon diagenesis.

progradation—The building forward or outward toward the sea of a shoreline or coastline (as of a beach, delta, or fan) by nearshore deposition of river-borne sediments or by continuous accumulation of beach material thrown up by waves or moved by longshore drifting.

regression—The retreat or contraction of the sea from land areas, and the consequent evidence of such withdrawal (such as enlargement of the area of deltaic deposition).

strandline—The ephemeral line or level at which a body of standing water, e.g., the sea, meets the land; the shoreline.

subaerial—Said of conditions and processes, such as erosion, that exist or operate in the open air on or directly adjacent to the land surface; or of features and materials, such as eolian deposits, that are formed or situated on the land surface. The term is sometimes considered to include fluvial.

subtidal—In a marine shoreline environment, below low tide (deeper than the intertidal zone).

transgression—The spread or extension of the sea over land areas, and the consequent evidence of such advance.

truncation—An act or instance of cutting or breaking off the top or end of a geologic structure or landform, as by erosion.

turbidite—A sediment or rock deposited from, or inferred to have been deposited from, a turbidity current.

unconformity—A substantial break or gap in the geologic record where a rock unit is overlain by another that is not next in stratigraphic succession, such as an interruption in the continuity of a depositional sequence of sedimentary rocks.

valley fill—Sediment deposited in a valley or trough by any process; commonly, fluvial channel deposition is implied.

wackestone—A mud-supported carbonate rock (carbonate mud) having >10% clastic grains.

Appendix 5

Core Descriptions, Well Logs, and Digital Images of Select Rock Intervals for the Following Wells:

1. **Sunray DX No. W-11 Adams**
   SE¼SE¼NE¼ sec. 19, T. 5 N., R. 8 E.
   Upper Cromwell Sandstone and crinoidal wackestone/packstone
   Prepared cored interval: 2,725–2,766 ft

2. **Austin & Emrick No. 1-Steele**
   SW¼NW¼SE¼ sec. 30, T. 9 N., R. 9 E.
   Upper Cromwell Sandstone
   Detached offshore-marine bar
   Prepared cored interval: 3,352–3,402 ft

Sunray DX No. W-11 Adams

SE¼SE¼NE¼ sec. 19, T. 5 N., R. 8 E.

Core of Upper Cromwell Sandstone

Consists of sandstone and crinoidal wackestone/packstone; very shallow marine to subtidal?

Log depth: about equal to core depth

Described by: Richard D. Andrews

Note: vfg = very fine grained; fg = fine grained; mg = medium grained

Core depth *(in feet)*	Lithology and sedimentary structures
2,725–2,728.5	Sandstone, fg, some mg, quartz framework, heavily oil stained, indistinct bedding, very porous, a few scattered crinoid fragments.
2,728.5–2,729.5	Sandstone, fg to vfg, grayish-green, quartz framework tightly cemented with matrix calcite. Bedding is indistinct.
2,729.5–2,733.1	Sandstone, fg, oil stained, very porous; bed forms are either indistinct or consist of horizontal and/or small-scale cross bedding. Minor amounts of shale laminations and/or shale stringers highlight bedding. A few small crinoid fragments are visible.
2,733.1–2,736.2	Sandstone, fg to vfg. Variable light oil staining occurs in porous zones 2–3 ft thick alternating with tight, fossiliferous, calcareous zones (light gray-green) having numerous crinoid fragments 2–8 mm.
2,736.2–2,737.2	Sandstone, fg, oil staining, numerous wavy, black shale laminations partition thin beds of bioturbated? sandstone. Moderately porous.
2,737.2–2,740	Sandstone, fg to vfg, tightly cemented with calcite, light grayish-green. Cleaner sandy zones 2–4 in. thick are moderately porous and slightly oil stained.
2,740–2,743.8	Sandstone, fg to vfg, heavily oil stained and porous in places, numerous scattered crinoid fragments to 15 mm. Bedding is horizontal to wavy (ripples?). More highly bioclastic zones are heavily cemented with calcite and are lighter colored. Some strata is missing between 2,740 and 2,741.
2,743.8–2,746.8	Crinoidal sandstone, fg to vfg, grayish green, horizontal to low-angle cross bedding, faint black shale laminations, numerous crinoid fragments supported in quartz dominated framework. Very limy and tight.
2,746.8–2,749.2	Sandstone, fg to vfg, with moderate porosity and minor oil staining. Bioturbation has destroyed original shale laminations, which appear now as irregular shale stringers.
2,749.2–2,752.5	Wackestone or bioclastic sandstone, grayish green, vfg to fg sand and crinoid fragments mostly <5 mm bonded by calcite matrix cement. Bedding is irregular, some burrows and bioturbation confined to more sandy strata.
2,752.5–2,756.8	Sandstone, fg, oil stained, indistinct bedding, possibly bioturbation, good porosity.
2,756.8–2,759	Limestone (wackestone or packstone) with crinoid fragments to 12 mm, grayish-green, some interbedded black shale.
2,759–2,761.5	Sandstone, vfg, interbedded with thin beds and laminations of black shale. Wavy and irregular bedding. Flowage at base.
2,761.5–2,762.5	Wackestone, dark grayish green with many crinoid fragments to 17 mm.
2,762.5–2,766.5	Sandstone, fg to vfg, heavily oil stained, soft sediment deformation (flowage), moderately porous.

Sunray DX No. W-11 Adams

(SE¼SE¼NE¼ sec. 19, T. 5 N., R. 8 E.)

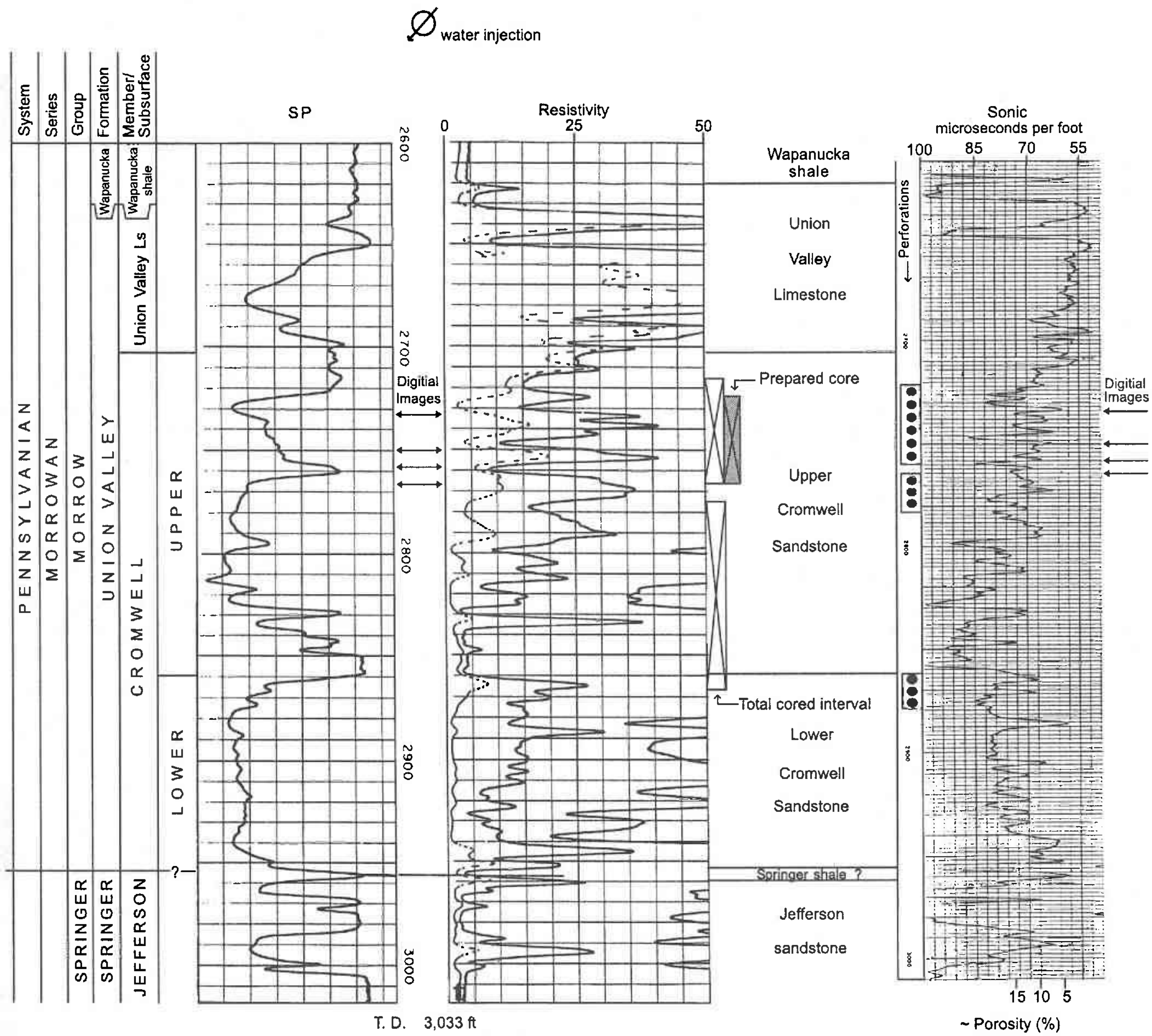
Reservoir cored: Upper Cromwell Sandstone

Depositional environment: Very shallow marine shelf bar, possibly subtidal

Core depth: 2,275–2,766 ft

Log depth: about core depth

KB: 899 ft



T.D.: 3,033 ft

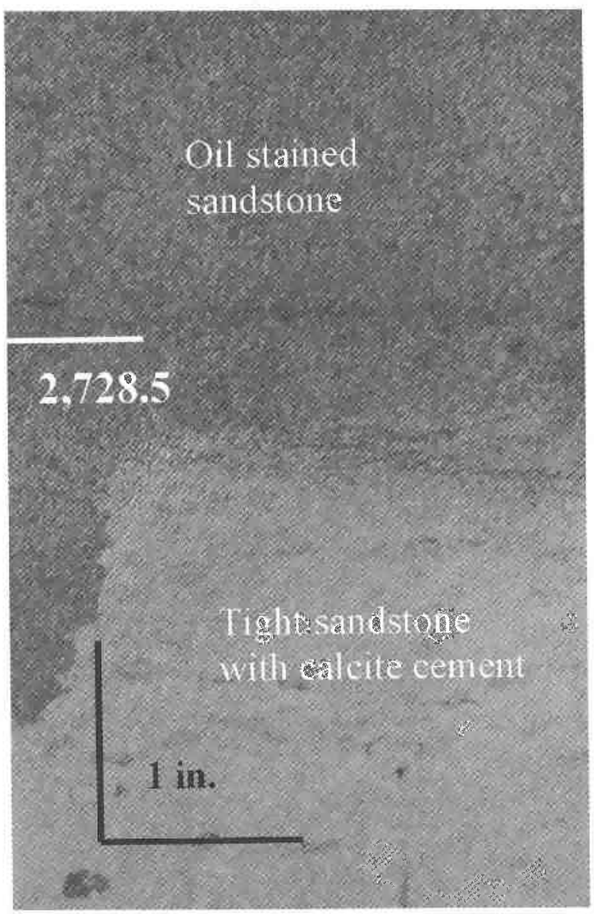
Sunray DX No. W-11 Adams

(SE¼SE¼NE¼ sec. 19, T. 5 N., R. 8 E.)

UPPER CROMWELL SANDSTONE

Main features: This core consists of fine-grained sandstone with various amounts of bioclastic (crinoids) debris. It has visual and clastic attributes similar to Morrowan outcroppings in the Ozark Uplift of northeast Oklahoma. The purpose of showing this core is to show similarities between outcrop and subsurface Cromwell (see digital pictures of outcrop in figures included in regional overview, Part I of this report). This core also is useful to demonstrate the variable nature of porosity and oil staining, and make it visually apparent what causes such reservoir characteristics. Additionally, sedimentary structures are useful in the interpretation of depositional environments—a skill necessary to better understand reservoir quality, extent, and composition.

The amount of skeletal material in this core contributes to calcite cementation, which is proportional to the amount of oil staining. Coloration changes from brown (oil-stained, high porosity) when there is little bioclastic material to a light grayish-green (calcite cementation, tight) when there is a lot of crinoid fragments. Additionally, trace fossils such as vertical borrows, and bioturbation are indicative of shallow marine conditions.

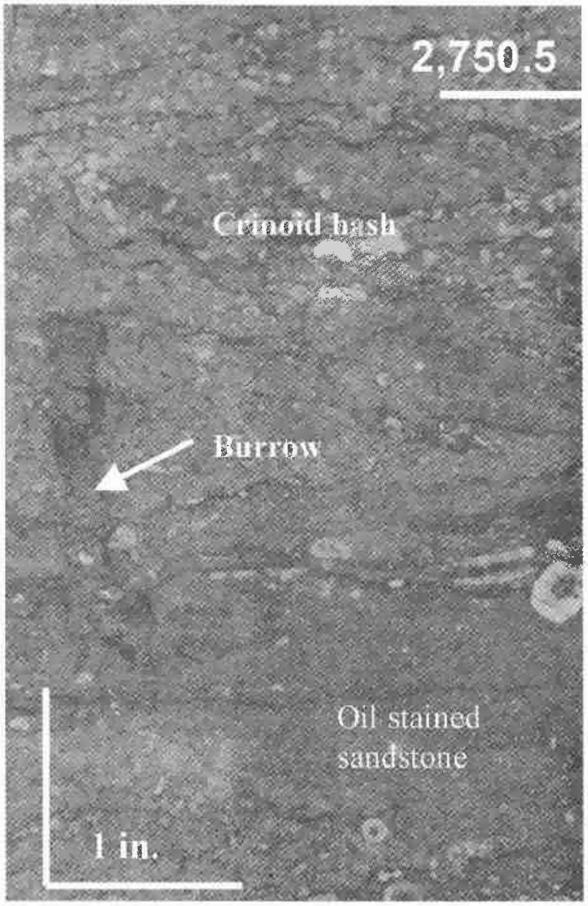


Core depth: 2,728.5 ft
Log depth: ~2,728.5 ft

Middle bar facies: Represented by fine-grained, horizontal-bedded sandstone. The upper part of core has excellent porosity and pronounced oil staining. This is contrasted with the lower half that is very light colored and consists of tight sandstone having calcite cement. And extension of the porous sandstone is shown dipping down into the tight sandstone on the left part of the image. Such changes in reservoir qualities can be interpreted from well logs if such characteristics are at least a few feet thick and therefore within detection limits of modern logging tools. The absence of high-angle cross bedding precludes this strata from being interpreted to belonging to the upper bar facies.

Sunray DX No. W-11 Adams

(SE¼SE¼NE¼ sec. 19, T. 5 N., R. 8 E.)

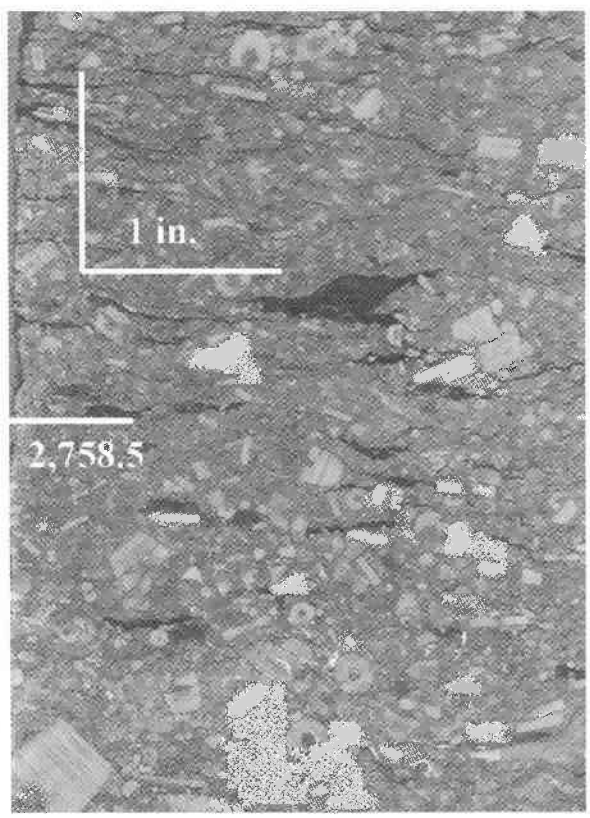


Core depth: 2,750.5 ft
Log depth: ~2,750.5 ft

Landward bar edge?: Consists mostly of fine-grained sandstone with scattered zones containing rafted crinoid fragments. Bedding is horizontal or slightly wavy and may represent remnant ripples. The upper half of the sample is lighter colored because of matrix calcite cement corresponding to large amounts of fossil material. The lower half of the sample contains less fossil material, is more porous, and is slightly oil stained. A vertical burrow almost 2 in. deep cuts through the sandstone in the left-center part of the core. The textural appearance of this sample and clastic composition indicates a high-energy marine environment. The crinoids lived and died in a very shallow, subtidal, low-energy marine shoreline environment. Storm or tidal currents destroyed the outer, deeper parts of this environment and transported the fossiliferous material along with sand farther away from shore. The trace fossil responsible for the vertical burrow is not specifically identified, but such types are common to dynamic shallow marine bars characterized by rapid deposition.

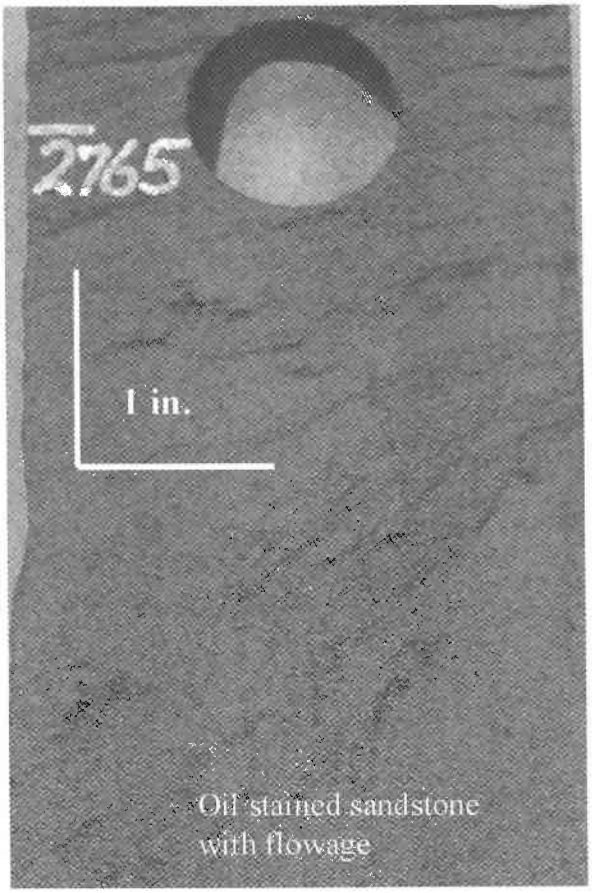
Core depth: 2,758.5 ft
Log depth: ~2,758.5 ft

Bar margin, interbar, or lower bar facies: Represented by framework constituents consisting mostly of crinoid fragments, and secondly, very fine grained sandstone. Matrix material consists of mud and calcite cement. This greenish-gray appearing sample is probably a wackestone or packstone, depending on specific framework and matrix compositions. The reduction in the amount of sand and higher clay content indicates that this strata is sand-starved either because the environment of deposition was in slightly deeper waters or the area simply was adjacent to or in between active bars. The total random orientation of crinoid fragments and lack of graded bedding again indicates a random, rapid deposition event.



Sunray DX No. W-11 Adams

(SE¼SE¼NE¼ sec. 19, T. 5 N., R. 8 E.)



Core depth: 2,765 ft
Log depth: 2,765 ft

Middle or main bar facies: Shows strata consisting almost entirely of quartz sandstone. The dramatic soft-sediment deformation (flowage) is noted by the curvy, dipping-to-the-left dark streaks. These were formed by deformation of shale laminations in response to loading and slumping or possibly dewatering following a period of very rapid deposition. The near absence of fossiliferous material indicates an environment farther from protected shoals that harbored marine fauna growth. This sandstone interval also represents an older cycle of deposition as compared to the sandstone interval represented by the above three images.

Austin & Emrick No. 1-Steele

SW¼NW¼SE¼ sec. 30, T. 9 N., R. 9 E.

Core of Upper Cromwell Sandstone

Consists of a coarsening-upward sequence of sandstone and shale; detached off-shore bar

Log depth: about core depth

Described by: Richard D. Andrews

Note: vfg = very fine grained; fg = fine grained; mg = medium grained

Core depth *(in feet)*	Lithology and sedimentary structures
3,352–3,365	**Upper bar facies:** sandstone, mostly fg (upper-end), almost pure quartz with silica cement—no calcite cement, medium- to well-sorted, subrounded to subangular grains. High-angle cross bedding predominates with interspersed zones having horizontal bedding. Shale laminations are sparse. Excellent porosity, no burrows or bioturbation.
3,365–3,373	As above, increasing amount of shale laminations, possible ripple bedding, and some high-angle cross bedding. Occasional rip-up clasts are present. Reddish alteration at 3,371.7 ft and 3,372.7 ft probably due to siderite alteration. Very good porosity. Vertical fracture at 3,371 ft.
3,373–3,375.7	**Lower bar facies:** sandstone, fg to vfg, framework constituents mostly quartz, numerous black shale laminations define bedding that is mostly horizontal and/or wavy (ripples?); infrequent cross bedding. Porosity decreases with depth. Very minor burrowing.
3,375.7–3,378.8	Sandstone, vfg to fg, mostly quartz framework, abundant shale laminations and some bioturbation and burrows.
3,378.8–3,400	**Transition zone:** interbedded vfg sandstone and thin black shale beds/laminations. Local iron staining from siderite alteration at 3,379.25 ft, 3,379.9 ft, 3,380 ft, 3,393.2 ft, and 3,396.9 ft. Ripple, irregular, and horizontal bedding. Abundant bioturbation and burrows. Clay and silt increasing with depth. Poor porosity.
3,400–3,402.5	**Open marine:** mostly black shale.

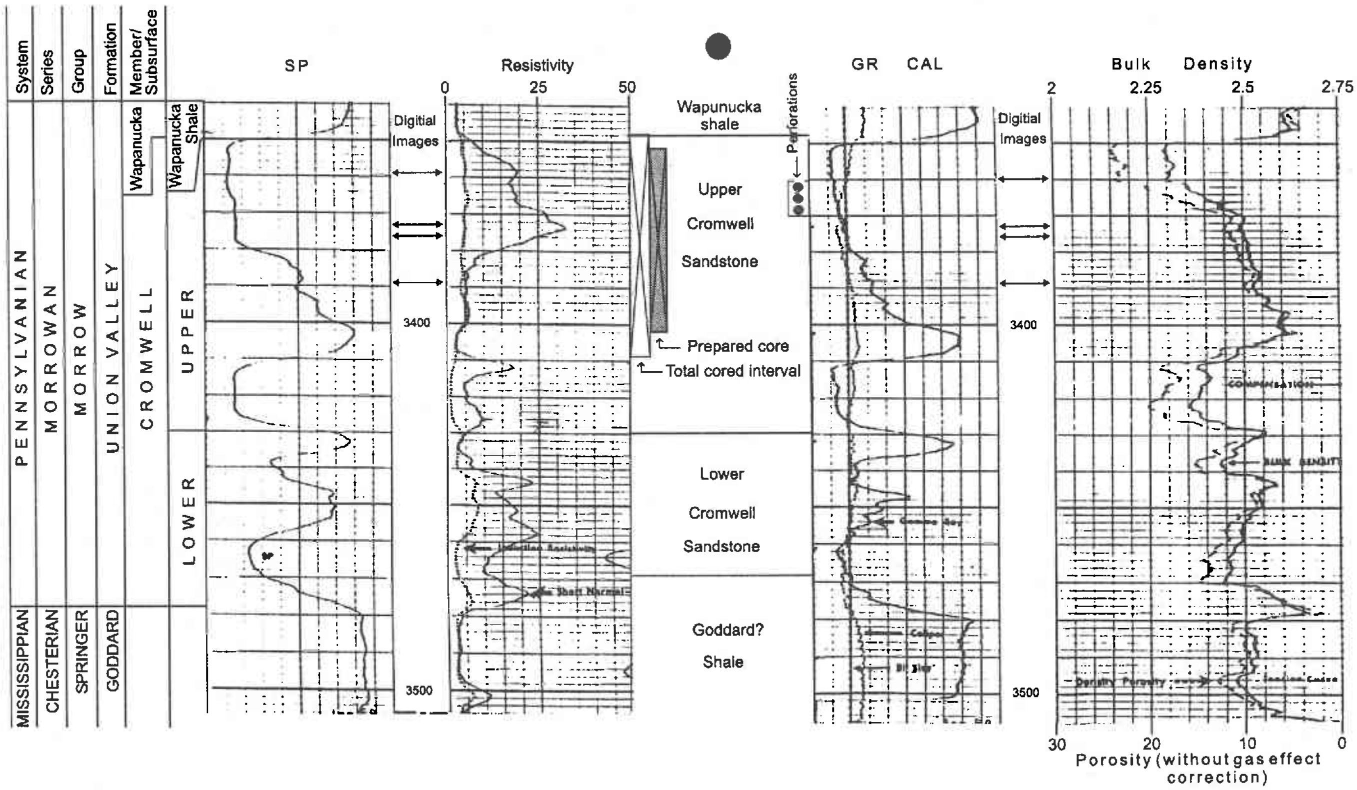
Austin & Emrick No. 1-Steele

(SW¼NW¼SE¼ sec. 30, T. 9 N., R. 9 E.)

Reservoir cored: Upper Cromwell Sandstone

Depositional environment: Detached offshore-marine bar

Core depth: 3,352–3,402 ft
Log depth: about core depth
KB: 786 ft

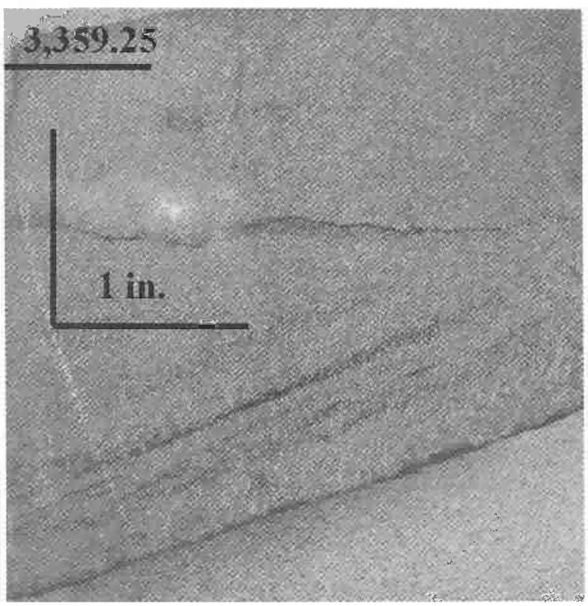


Austin & Emrick No. 1-Steele

(SW¼NW¼SE¼ sec. 30, T. 9 N., R. 9 E.)

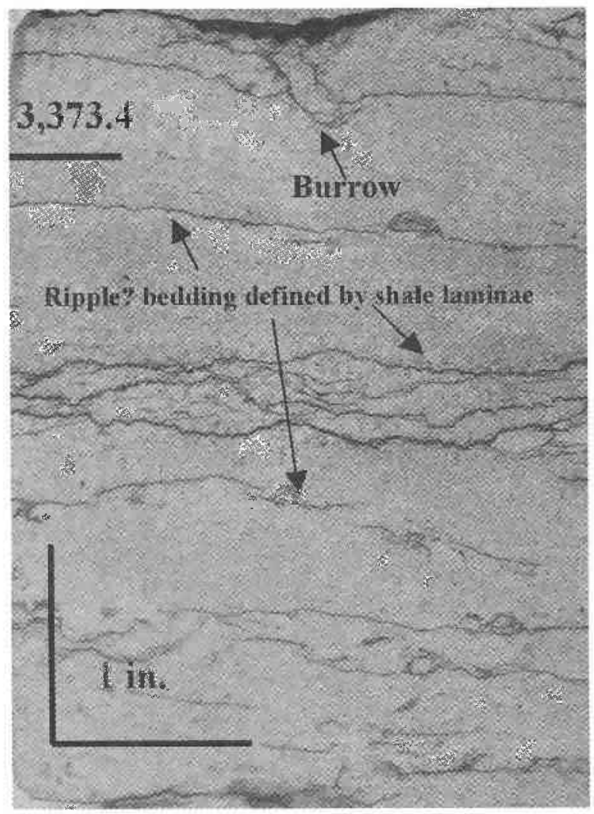
UPPER CROMWELL SANDSTONE

Main features: This core is an excellent example of a detached, off-shore marine bar and is typical of those productive throughout much of the Cromwell play in the western part of the Arkoma Basin. The sandstone interval has a coarsening-upward textural profile typical of marine bars. Because of this, the core exemplifies specific zones or facies as determined from key sedimentary structures and textures: an upper bar facies characterized by clean, fine-grained sandstone having high-angle cross bedding, a lower bar facies characterized by clean, fine to very fine grained, horizontal or rippled bedded sandstone, a bar transition zone composed of burrowed, bioturbated sandstone interbedded with shale, and an open marine facies dominated by black fissile shale. As can be determined from the accompanied well log, the best reservoir in this type of deposit always occurs in the upper and lower bar facies above the bar transition zone. Porosity in this sandstone probably exceeds 18% in places.



Core depth: 3,359.25 ft
Log depth: ~3,359.25 ft

Upper bar facies: Consists of fine-grained sandstone having conspicuous high-angle cross bedding. Because of higher current energy in the shallowest waters submerging a bar, cross bedding is a common sedimentary structure in the upper part of a bar sequence. Such bedding may be hard to see when there are no dark laminae defining bed-sets, whereas it is apparent in this image because of the inclination of the faint black shaly layers. This part of the bar was probably deposited in <20 ft water. Because of the overall lack of clay in this zone, the gamma-ray log looks "clean" and has very little response.

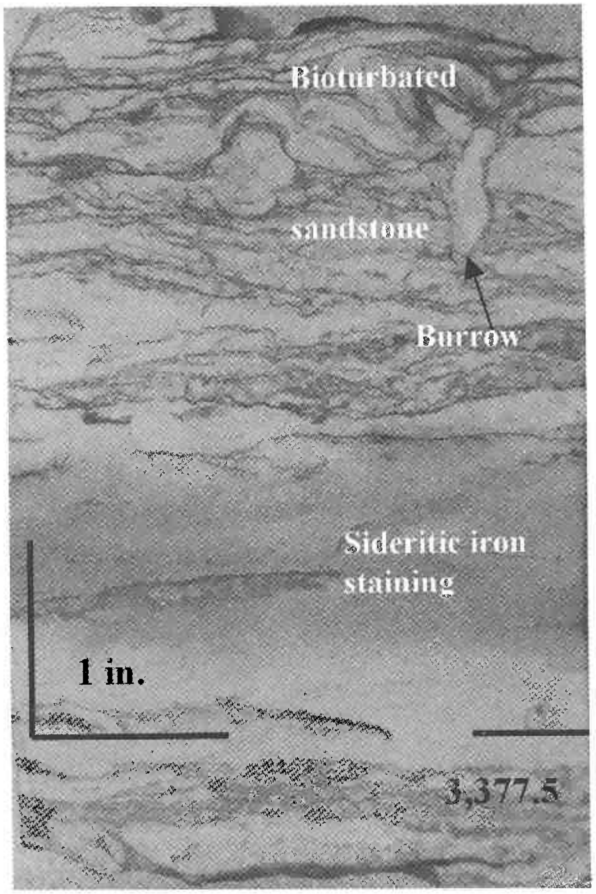


Core depth: 3,373.5 ft
Log depth: ~3,373.5 ft

Lower bar facies—upper part: Consists of fine to very fine grained sandstone having wavy and possibly ripple bedding. Bedding is defined by black shale laminations. One small vertical burrow can be seen at the top-center of the image. The lack of persistent high-angle cross bedding and predominance of lower-energy bed forms are consistent with the lower bar facies that are typically deposited in water depths a few tens of feet deeper than the upper bar facies but above fair-weather wave base of ~50 ft.

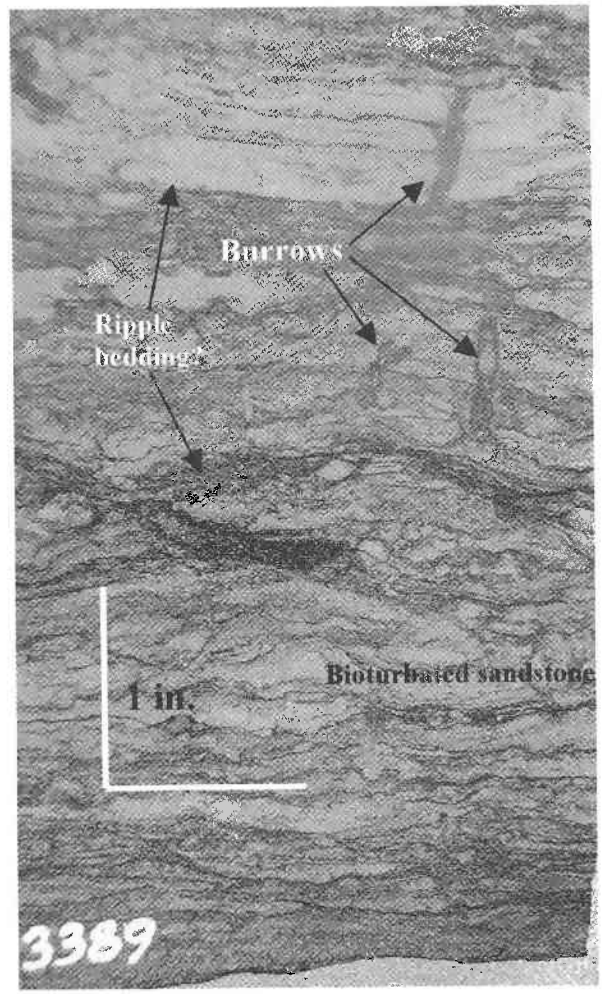
Austin & Emrick No. 1-Steele

(SW¼NW¼SE¼ sec. 30, T. 9 N., R. 9 E.)



Core depth: 3,377.5 ft
Log depth: ~3,377.5 ft

Lower bar facies—lower part: Consists mostly of very fine grained sandstone with increasing amounts of shale laminations. The upper part of image shows burrowing and bedding is somewhat destroyed by the effects of bioturbation. Just below this zone is a thin sandstone interval having iron staining. The darker clasts in this zone "fizz" slightly—an indication of siderite (iron carbonate). Siderite is generally an unstable constituent in highly oxidizing environments, so it is not commonly preserved in the top part of a marine bar, rather, it is more stable in oxygen-deficient environments that are generally of deeper origin. Because of the increasing amount of interbedded and interstitial clay in this zone, the gamma-ray log has an increasing response with depth.



Core depth: 3,389 ft
Log depth: ~3,389 ft

Bar transition zone: Is characterized by abundant shale interbedded with thin, very fine grained sandstone lenses. The large amount of clay in this zone causes a high gamma-ray response on the log. Conspicuous sedimentary structures include numerous vertical burrows and ubiquitous bioturbation. The transition zone commonly has ripple bedding, since it is still subject to strong currents above storm wave base of ~100 ft. Below the transition zone, the strata becomes entirely or nearly all shale as it is far removed from depositional sources and active depositional processes.